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Anode phenomena of direct current arcs between moving electrodes.

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ANODE PHENOMENA OF DIRECT CURRENT ARCS BETWEEN MOVING ELECTRODES

PHILIP S. McMANUS

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THESIS
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PHILIP S. McMANUS

ANODE PHENOMENA
OF DIRECT CURRENT ARCS
BETWEEN
MOVING ELECTRODES

by

Philip S. McManus

Leiutenant Commander

United States Navy

An essay submitted to the Advisory Board of Engineering of The Johns Hopkins University in confromity with the requirement for the degree of Master of Science in Engineering.

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The author wishes to take this opportunity to express his appreciation for having been given the opportunity to attend The Johns Hopkins University, to extend the graduate training that had started at the United States Naval Postgraduate School. He also wishes to acknowledge the opportunities afforded him to further his professional knowledge by his being permitted to associate himself with the extensive electric arc research being conducted at The Hopkins, under the sponsorship of the Navy Department of the United States. It is hoped that this paper may, in some small way, assist in the better understanding of some of the mechanisms of the electric arc.

To Dr. W. B. Kouwenhoven, Dean of the School of Engineering and to Dr. T. Benjamin Jones, Assistant Professor, the School of Engineering, The Johns Hopkins University, goes the deepest gratitude for their wise suggestions and guidance and without whose interest, this paper would not have been possible.

The invaluable assistance of Bernard List and John Dzimianski, who assisted in the gathering of some of the experimental data is deeply appreciated, as were their many constructive criticisms. All the graphs in this paper were prepared for publishing by Bernard H. List.

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INTRODUCTION

The discovery of ~~the~~ the electric arc by Davy[1] opened a vast field for the investigation of the phenomena of the arc discharge. Today, more than a century after its discovery, there are still many hidden secrets concerning the mechanism of the arc operation. Although many facts concerning the exact mechanism of the operation of the arc are unknown, the arc is a convenient and widely employed tool of many industrial and scientific processes. Frequently unwanted arcs will form in electrical circuits and equipment and they are usually accompanied by undesirable effects. It would seem evident that, if all the mechanisms of the arc were known, then the desirable effects of the arc could be utilized to their greatest extent while the undesirable effects could more readily be controlled. It was in an effort to find an explanation for some of the characteristics of the arc mechanism that the work described in this paper was undertaken. Because of the nature of the experiments conducted, this study is primarly directed towards investigating the effects of the arc at the anode.

Before proceeding with a discussion of these investigations it appears advisable to briefly outline a few of the presently accepted facts concerning the arc mechanism and operation.

(a). Arcs may be formed between either solid or liquid conductors.

(b). An arc can not exixt in a complete vacuum, but occurs only when an atmosphere of some kind fills the space between the electrodes.

(c). Arcs may be initiated by:-

(1). Transition from a glow discharge.

(2). Initiation by a spark.

(3). Initiation by seperation of contacts.

(4). Heating one or both electrodes to incandescence.

(d). The arc is characterised by high current densities.

(d). The current in the arc is carried by both electrons and positive ions.

(f). No maximum limiting value of arc current appears to exist.

(g). The potential drop associated with the arc generally is in the range from 20 to 100 volts and is usually non-linear with respect to the arc current.

(h). The potential drop associated with the arc is usually considered as being composed of three separate and distinct voltage drops, namely:-

(1). The Anode Drop.

(2). The Plasma Gradient.

(3). The Cathode Drop.

(i). Emission of electrons from the cathode is a necessary requirement for the ~~arc~~ arc to exist.

(j). Current densities of the order of 50,000 amperes per square centimeter at the cathode spot have been measured[5].

(k). Current densities of 500 amperes per square centimeter have been measured in the arc plasma[5].

(l). Apparent current densities of about 25,000 amperes per square centimeter have been calculated for the anode spot[26].

Recently an extensive series of investigations, under the sponsorship of the Ofice of Naval Research, have been undertaken at the

Johns Hopkins University, for the purpose of attempting to add further information to the above partial list of facts known about the electric arc. One phase of these investigations, conducted with the high current d.c. arc, were based on certain phenomena first observed by Kouwenhoven[6]. It was found that, when an arc is formed between a stationary cathode in the form of a rod and a moving anode in the form of a flat metalic surface, a record of discrite spots of melted metal would be left on the anode. These spots have been called Anode Spots and because of the method by which they are obtained, they effectively spread, in space, the action of the arc on the anode. This 'spreading in space' of some of the effects of the arc energies has aided in the study of certain arc phenomena, which had previously been obscured by the intense concentration of energy in a very small area at the anode.

From a suggestion by Kouwenhoven and Jones[6,7,8,11] who had developed the moving electrode technique for speeds approaching 4,000 feet per minute and in an effort to extend the speed range obtained by Spann[26], a new apparatus was designed and built by the author for the purpose of extending the speed range to 10,000 feet per minute. The apparatus was constructed in such a manner as to permit increasing this speed range to two or three times the value quoted above, by the simple modification of the installation of an anode wheel made from a suitable material.

As a brief background for the discussion of the investigation conducted by the author in the field of 'Anode Spots', the following partial summery of the work of the earlier investigations of the anode spot phenomena is presented[6,7,8,11,25,26,27]. These experiments have been carried out for high current d.c. arcs with relative motion of the elect-

rodes up to an upper limit of 4,000 feet per minute for mild steel anode tapes. Anodes of aluminum, copper and zinc tapes have also been used up to speeds of 2,000 feet per minute. Cathodes of carbon, tungsten, steel and copper have been employed. At all except the very low speeds the arc forms discrete spots on the anode rather than a continuous track. When the moving plane metal surface is made negative with respect to a stationary anode rod the cathode spot appears to trace a continuous track on the plane cathode surface. In the latter case the arc is much less stable. For the mild steel anodes apparent current densities of the order of 24,000 amperes per square centimeter have been observed[25].

In order to determine the anode materials to be used in this investigation, a study of the results of the earlier investigations of the high current d.c. arc, in which the moving electrode techniquehad been employed, was conducted. This study indicated that the variation, with electrode speed and arc current, of the number of anode spots formed per inch and the individual anode spot areas for aluminum, steel and zinc anodes all appeared to fall into the same pattern. However, for copper anodes the variation of the number of anode spots formed per inch and the individual anode spot areas did not fit this same pattern. Because of this difference, it was decided to use copper as one of the anode materials employed in this investigation. Further, because of the marked similarity in the variation in the measurable arc variables for aluminum, steel and zinc anodes and in view of the ease of handling it was decided that aluminum would be used as the second anode material employed in thes investigations.

EXPERIMENTAL APPARATUS

The experimental apparatus designed, constructed and operated by the author for the purpose of obtaining additional information about the high current d.c. arc anode spot phenomena is described in the following section. The description is perhaps best accomplished by first describing the individual physical components of the apparatus and then coorelating these components by giving a detailed explination of the experimental technique evolved for their use.

Design requirements

The physical design of the experimental apparatus was controlled by the following requirements:-

(a). The apparatus had to be capable of producing relative speeds up to ten thousand feet per minute between a cathode in the form of a rod and an anode in a form that should closely approximate an infinite plane, while maintaing a preset distance between the anode surface and the tip of the cathode.

(b). The cathode and anode mountings had to be of such a nature as to permit mounting the various kinds of cathode and anode materials as might be desired by the investigator. Moreover, these mountings had to be electrically seperated one from the other except through the arc path from the anode to the cathode.

(c). The electrical portion of the apparatus had to be capable of supplying, distributing, measuring and recording currents and voltages up to six hundred amperes and one hundred volts respectively.

(d) The controls of the apparatus had to be sufficiently simple and arranged in such a manner as to permit a single investigator to easily operate all controls required for a particular experiment.

(e). If practicable the magnetic properties and the physical arrangement of the apparatus had to be of such a nature as to cause the least disturbance to the arc.

GENERAL DESCRIPTION OF THE APPARATUS

Figure 1 shows a general view of the apparatus assembled in an attempt to fulfill the above requirements. The apparatus consists of the following main assemblies and equipment; (a) the anode assembly, (b) the cathode assembly, (c) the arc starting mechanism, (d) the arc power supply, (e) the control panel, (f) the anode speed, arc current and arc voltage measuring equipment and (g) the high speed camera for high speed photographic recording.

The anode assembly consists essentially of a large cast iron wheel with its shaft horizontal. The anode material, after being formed into a continuous circular tape about six inches in width, was mounted on the periphery of the wheel. The rotation of the wheel carried the anode past the cathode mounted on a carriage slung from two parallel guides. This mounting permitted the cathode carriage to be drawn in the direction of the axis of rotation of the anode wheel.

The cathode mounting was constructed so that the extension of the centerline of the cathode rod intersects the axis of rotation of the anode wheel and is perpendicular to the anode at their point of intersection. The combination of the rotation of the anode tape and the linear motion of the cathode can be adjusted to cause the intersection of the cathode rod centerline, extended, and the anode surface to trace out a helicial path on the anode surface, thus spreading in space the arc phenomena recorded at the anode surface.

~~ANODE ASSEMBLY DETAILS~~

ANODE ASSEMBLY DETAILS

In order to minimize any adverse effects of vibration, the anode wheel mounting was made as sturdy as practicable. The mounting consists of a metal table composed of four cast iron supports bolted to the floor and topped with a steel plate four feet long, three feet wide and one inch thick. The anode wheel axle is three and one quarter inches in diameter, aapproximatly four and one half feet long and is carried by two high speed Timpken roller bearings. The axle bearings are securely bolted to the steel table top by means of three quarter inch thru bolts. The cast iron anode wheel is pressed on this shaft and locked into place by means of a one half inch square key. The anode wheel and axle assembly, with its mounting base, weighs approximately three quarters of a ton. The periphery of the anode wheel has a face seven and one half inches wide with a slight crown. The ~~maximim~~ maximum diameter at the center of the wheel face is thirty five and one half inches. This diameter decreases to 34.444 inches at the outer edges of the wheel face. By making the inner circumference of a continuous anode tape 111.537 inchs long, the tape could be securely locked on the periphery of the anode wheel by utilizing the taper of the face of the anode wheel and forcing metal shims, thirty thousandths of an inch thick, under the outer edge of the anode tape. The anode wheel is driven by three 'vee' belts from a three horsepower, direct current, variable speed motor. To prevent the large arc currents from flowing through the anode shaft roller bearings, the electrical connection from the anode to the arc current generator circuit wiring is completed through a slip ring, mounted on the anode wheel driving shaft, and four carbon brushes. The total brush contact area is approximatly

ten square inches.

The anode driving motor is rated at three horsepower at 1250 RPM and at full load draws eighteen and one half amperes from a 220 volt supply. By means of the pulley drive the anode wheel can be driven up to 1200 RPM, corresponding to a relative speed of the anode surface past the cathode of approximately eleven thousand feet per minute. To provide for the range of anode speeds desired, the stator field windings of the anode drive motor were connected to the 220 volt direct current supply while the armature circuit was arranged so as to permit connecting the armature to either the 110 volt or the 220 volt direct current sources. Additional speed control is provided by including a variable series resistor in the armature circuit. The resistor used is a standard laboratory lamp bank and is connected so that, in addition to providing the speed control desired, it can be switched so as to provide a dissapative load for dynamic brakeing of the anode wheel at the conclusion of a run.

CATHODE ASSEMBLY DETAILS

The cathode assembly consists of a carriage, containing an electrode holder, which is mounted on two one half inch round guides thus permitting the cathode carriage to be moved parallel to the surface of the anode in a direction perpendicular to the direction of motion of the anode. Figures 2 and 3. show the details of the cathode assembly. The cathode carriage is drawn along its guides by means of a pulley wire connected to the cathode drive motor pulley wheel. The cathode drive motor is secured to the lower surface of the cathode assembly mounting base. In order to prevent the pitch of the helix traced on the anode,

by the anode spots, from becomming too small and thus, by the overlapping of the anode spots, obscure the desired record of anode spot phenomena and further, to insure that the maximum number of identifiable traces CONT'D be obtained with a minimum expenditure of anode material, it is necessary to correlate the speed of the cathode carriage with the speed of the anode. To provide the range of speeds required, the cathode drive motor has a variable series resistor connected in its armature circuit. In order to prevent damage to the cathode carriage and the instruments mounted thereon, a drive pulley-wire disconnect cam is installed to unhook the cathode carriage from the cathode drive wire when this carriage has traveled the full distance past the anode. As a further precaution, a knife switch, located in the cathode drive motor armature circuit, is mounted so that it will be opened by the cathode carriage when the carriage has traveled beyond the anode. The entire cathode assembly is mounted on a wooden base eight feet long, eight inches wide and two inches thick. This wooden base performs the dual functions of providing a rigid mounting for the cathode assembly and insulates this assembly from the anode assembly.

THE ARC STARTING MECHANISM

Figures 2. and 3. show the mechanism used to start the arc between the moving anode and the stationary cathode. This assembly consists of a carbon rod mounted in a pivot arm which is positioned so that when the pivot arm is rotated, by means of its remote control line, the carbon rod will swing up and simultaneously touch the anode and the cathode thus completing the arc circuit. This shorting rod is held in position

long enough for the cathode to heat up sufficiently for the arc to maintain itself after the shorting rod has been permitted to swing back to its neutral position.

ARC POWER SUPPLY AND WIRING CONNECTIONS

The power supply used for the arc current is a General Electric, three hundred ampere, portable welding generator. This machine was designed as a constant current source and is equipped with controls for varing the current supplied, from a minimum of about 40 amperes to a maximum of about 425 amperes.

The wiring connections between the welding generator and the anode and cathode assemblies are made by means of six hundred ampere welding cable. This circuit contains four hundred ampere fuses to protect the welding generator. It also contains a heavy duty double pole knife switch to interrupt the arc current when desired.

MISCELLANEOUS RECORDING EQUIPMENT

The arc current is measured and recorded on an Esterline-Angus recording ammeter. The current shunts used with the recording ammeter ~~is~~ arc connected in the anode portion of the arc circuit wiring. The arc potential drop is measured and recorded by means of an Esterline-Angus recording voltmeter connected across the anode and cathode assemblies. The recording meters may be seen in the foreground of Figure 1. The meter shown in Figures 2. and 3. is a Triplett milliammeter. This milliammeter was connected across a current shunt in the anode wiring circuit and is used to indicate arc current. Its location was choosen so that

it would be in the field of view of the high speed camera used to photograph the arc, thus providing photographic coorelation between the instantaneous appearance of the arc and the arc current.

The 16 mm Kodak high speed motion picture camera, with its 63 mm, f/2.7 lens, shown in Figure 1. is used to photograph the arc. These high speed photographs may be used to 'spread in time' the action of the arc.

The anode wheel rotational speed is measured by means of the Strobascope with its connected Strobalux, both of which may be seen in Figure 1.

EQUIPMENT LIMITATIONS

The one serious shortcoming of the experimental apparatus is the upper limit of arc current that can be supplied by the single welding generator. This limitation was particularly serious at the higher values of anode speed, where the maximum value of about 350 amperes ~~available~~ obtainable was only a few percent greater than the minimum current required to maintain a stable arc. In fact, although the apparatus, as designed and constructed, would permit anode speeds of 10,000 feet per minute, it was not possible to investigate the arc phenomena at anode speeds greater than 8,000 feet per minute because of this limitation.

The natural mechanical vibrational frequency of the anode assembly was excited at anode speeds of 4,000 and 6,000 feet per minute. The amplitude of the vibrations produced at these speeds was large enough to make signifacant changes in the electrode seperation. For this reason, no attempt was made to obtain data in the neighborhood of these speeds.

One further minor limitation seems worthy of mention. The maximum

objective magnification obtainable in the microscope used to measure the anode spot diameters was six power, with a field of view of approximately 1/50 square centimeters. Although a smaller field of view would not have been acceptable, the relatively small objective magnification of the microscope restricted the accuracy of measurements of the anode spot diameters to about plus or minus 1/500 centimeters. This accuracy limittation became significant only when measuring spot diameters of the order of 1/50 centimeters or less. Fortunately, anode spot diameters of this magnitude were encountered only at the very highest speeds investigated and then only on the copper anodes.

EXPERIMENTAL TECHNIQUE

This section of this paper is devoted to a discussion of the steps taken in the gathering of the experimental data. At appropiate points in the discussion, detailed descriptions of the necessary preperations preliminary to the runs are included as are explanations of the special precautions that were observed during the gathering of the experimental data.

Anode tape material of copper and aluminum were cut from commercially pure metals and formed into continuous hoops. These hoops were six inches wide and had an inner circumference of 111.537 inches, corresponding to the maximum outer diameter of the anode wheel. In order that the tapes might be accurately constructed, a jig for holding the tape material during layout was built. The jig securely held one end of the tape material at a scribe line while the material was unrolled towards the second scribe. Prior to cutting the tape at the second scribe, a roller was passed over the tape to insure that the tape had not humped at any point between the two scribe lines. After accurately marking the tape metal, the section was cut from the roll two inches past the scribe line. The two additional inches of the tape metal were then used as a lap joint to form the tape into a continuous hoop. Although it was impractical to determine the exact diameter of the circular hoops thus constructed, from the close fits obtained, it was estimated that the maximum deviation of the diameter of any anode hoop, from the desired diameter of 35.500 inches, was not more than plus or minus five one thousandths of an inch. The ends of the aluminum tapes were joined

together by spot welding, after one end of the tape had been securely clamped at the scribe mark approximately two inches from the other end of the tape. Each joint was secured by means of sixty spot welds. No evidence of any tendency for the joints to fail due to the centrifugal or tangential forces developed by spinning the tapes mounted on the anode wheel was noted.

The copper tape lap joints were made by means of low melting point solder, consisting of fifty percent tin and fifty percent lead. The lapped portions of the joint were first cleaned with dilute hydrochloric acid and then tinned to insure a ~~unifor~~ uniform joint. After properly locating the relative positions of the ends of the copper tapes, they were clamped into position and ~~place~~ placed in a press. The joint was then heated above the melting point of the solder by means of bunsen burners. While the solder was in the liquid state, the lap joint was subjected to a compressive pressure of about ~~fout~~ four tons per square foot. This compressive pressure squeezed out the excess solder and insured a ~~unifor~~ uniform flat joint. Every effort was made to prevent the face of the copper anode that was to be exposed to the arc from being coated with solder. However, it was found, that in order to insure a tight joint at the edges of the lap, it was necessary to extend the solder tinning coat approximately one eight to one quarter inch past the edge of the lap joint. As in the case of the aluminum tapes, no failures of the lap joints were noted.

In order to mount the anode tapes an the anode wheel, a jig was constructed that would hold the flexible anode tapes in a circular shape while these tapes were being jockied into position on the anode wheel. This jig may be seen in the background of Figure 1.

After the tapes were centered on the face of the anode wheel they

were locked into place by forcing aluminum shims, thirty thousands of an inch thick, under the outer edges of the tapes. The anode wheel was then rotated slowly, by hand, and the distance between the anode tape and the cathode carriage was checked to insure that the anode tape surface had no eccentricity. Any eccentricity noted was corrected by the insertion of shim brass of the required thickness under appropriate portions of the anode tape. The preperation of the anode surface took four forms, namely:-

(a). A limited number of runs were made on both aluminum and copper anode surfaces with no special preperation except to wipe off the surface dust.

(b). A limited number of runs were made on both aluminum and copper anodes after the surfaces had been roughened slightly by rotating the anode surface against a steel wire brush.

(c). A few runs were made after the copper oxide had been removed from the copper anode surfaces by means of a dilute hydrochloric acid bath.

(d). The majority of the runs were made after the anode surfaces had been scrubbed with carbon tetrachloride. Part of the runs outlined in (b) above were made after the roughened surface had been cleaned with carbon tetrachloride and the remainder without this cleaning.

At this point it should be noted that all the quantitative data presented in this paper, except where specifically indicated, is based upon anode surfaces prepared as in (d) above.

In order to conserve the critical anode material, while obtaining

the large quantity of data required, the six inch widths of the anode tapes were divided into three parts by means of one quarter inch masking tape. In most cases this masking tape acted as an insulating strip and caused the arc to extinguish as the arc path was driven across the dividing strips. In a few cases, particularly for the higher values of arc current and the lower values of anode speed, it was found that the arc could not be made to extinguish at this dividing tape unless the width of the tape was increased to about three quarters of an inch.

The cathode material that was employed for the investigations, covered in this paper, was carbon in all cases. This carbon was formed into rods one quarter of an inch in diameter and approximately eight inches long. The tips of the carbon rods were cut off perpendicular to the axises of the rods. The carbon rod was inserted into the brass receptical on the cathode carriage, where it was held in place by four thumb screws. This method of securing the carbon rods prevented any motion of the rod in its receptical and provided a pressure contact for the arc current to pass from the cathode receptical to the carbon cathode. Prior to tightening the thumb screws on the cathode receptical, the tip of the carbon rod was placed one eighth of an inch from the anode surface. This adjustment was invariably made by means of a calibrated wedge that had been built for the purpose. At the conclusion of the run this distance was again measured. If, due to the vaporization of the carbon or any other cause, the distance between the anode surface and the cathode tip had increased by more than five percent during the course of a particular run, the data obtained therefrom was discarded and the run repeated. Due to the relatively

high rate of combination of the carbon with the oxygen of the surrounding atmosphere, particularly at the higher arc currents, the diameter of the cathode rod decreased appreciably in a very short time. In the intrest of reproduceability of results, the cathode diameter was measured prior to and at the conclusion of each run. If, during a run, it had decreased by as much as five percent the data was discarded and the run repeated with a shorter total burning time for the arc, thus bringing the cathode diameter change to within the maximum acceptable value.

After preparing the anode tape surface and properly positioning the carbon cathode rod, the cathode carriage was connected to the carriage drive pulley wire and the high speed motion picture camera was focused, if it were to be employed for that particular run. The anode wheel drive motor was then turned on and the anode wheel slowly brought up to speed by means of the variable series resistor connected in its armature circuit. The anode wheel speed was continuously determined by means of the strobascope. This strobascope had been calibrated with the aid of a synchronous motor. Because the strobascope's minimum flashing rate was approximately eight hundred per minute and because the accuracy of its internal scale increased from ninety eight percent, at the lower repetition rates, to better than ninety nine and one half percent at the higher values of scale setting, the anode wheel speed was measured by causing the strobascope to flash at six times the angular speed of the anode wheel. This method of determining the anode wheel speed permitted using the strobascope to measure wheel speeds from approsimately one hundred fifty revolutions per minute, with errors of less than two percent.

When the anode wheel had been steadied at the desired speed, the welding generator, used as the arc current source, was turned on and allowed to run for a short time to permit it to reach its maximum rotational speed. The recording voltmeter and ammeter, after being set for their maximum speed of paper travel (twelve inches per minute), were then turned on. The knife switch connecting the the welding generator to the anode and cathode wiring circuits was then closed. The control line to the arc starting mechanism was then manipulated so as to swing the carbon shorting rod up into position to short the air gap between the moving anode tape and the cathode electrode. After momentarily shorting the anode to the cathode, the arc starting control line was released and the windage from the anode wheel caused the shorting carbon to swing clear of the arc.

If high speed photographs were to be taken, the camera switch was then closed. The arc was allowed to burn for approximately three seconds while holding the cathode carriage stationary. This short time delay permitted the high spe d camera to begin to approach its maximum speed and further, permitted the welding generator to attempt to settle down under the suddenly applied load. After this short time delay the cathode drive motor was turned on causing the arc to trace out a helical path on the anode. During the initial preperation for the run, the variable series resistor in the armature circuit of the cathode drive motor, was set to give this helecal path a pitch of about one half inch. When the cathode traced its path over the anode insulating strips or when the cathode traveled beyond the face of the anode wheel, the arc would automatically itself. As the cathode carriage

moved further down its guides, it would first trip the knife switch in the cathode drive motor circuit and then eggage the cam that would disconnect the carriage drive pulley wire from the darriage. The approximate time that the arc would burn during any one run varied from four ~~fout~~ to eight seconds depending upon the amount of time that the cathode was allowed to remain stationary and the speed of the cathode carriage. Immediately after the arc extinguished, the anode wheel speed was again measured to insure that it had not varied during the run. The arc current generator was then shut down, the recording meters stopped and the dissipative load resistor, in the armature circuit of the anode motor, was connected to act as a dynamic brake to stop the anode wheel. When ~~when~~ the anode whe l stopped, the anode tape was checked for any possible looseness that might have developed during the run, the condition of the lap joint was inspected and the cathode diameter and the distance between the anode surface and cathode tip measured.

After cutting the anode tape from the anode wheel, it was numbered for positive future identification by means of metal numbering punches. The surface of the anode tape was then divided into ten inch lengths. The eleven inches of anode tape straddling the lap joit was excluded from this division. The total number of anode spots formed in each row of each ten inch section was counted and divided by ten to obtain the number of spots formed per inch. The number of spots per inch, calculated for each ten inch row, was then compared with the average value obtained from a consideration of all the ten inch rows. The values from those ten inch rows that differed from this average

by more than five percent were discarded and a new average calculated. This selective averaging was necessary because of two conditions encountered during the course of each run. First, when striking the arc and for about three seconds after ignition, the cathode assembly was held stationary. The burining of the arc during this period rapidly coated a narrow band of the anode surface with a heavy deposit of carbon. After putting the cathode assembly in motion the number of anode spots formed per inch was about ten percent higher than the average value for the run. This variation in the number of spots formed per inch decreased until the steady state value was reached after the cathode had moved approximately one half inch past that portion of the anode which had become coated with the heavy deposits of carbon. Second, As the cathode tip crossed over the insulating tape, used to divide the anode into sections, instead of the arc extinguishing immediately, the arc would continue to burn until the trailing edge of the cathode had moved about one eighth of an inch past the covered portion of the anode. During this brief period, the number of spots formed per inch would rapidly decrease to a value between twelve and two percent of the steady state value without any appreciable change in the recorded value of the arc current. This last phenomena was also observed to occur when the cathode tip moved beyond the face of the anode surface.

After the average value of 'spots per inch' had been determined, the major and minor axises of the individual spots were measured in the two ten inch rows of spots whose value of 'spots per inch' most closely approached the average value of the calculated 'spots per inch'

for the entire tape. The spot major and minor diameters were measured by means of a calibrated scale installed in the eyepiece of a microscope. The average area of the spots formed during each run was then determined by assuming that the spots were elliptical is shape. Figures 4. through 10. show the microscope calibrated scale superimposed on enlarged photographs of the aluminum and copper anode spots. Each major subdivision of the scale represents a measurement of one sixth of a millimeter, while each minor subdivision represents a measurement of 1/120 millimeter. To facilitate the measurement of the spot diameters, the heavy deposits of copper oxide surrounding the spots formed on the copper tapes were first removed by means of a dilute hydrochloric acid bath. Because of the difficulty of removing the aluminum oxide from around the aluminum spots, these spots were placed under the microscope for examination and spot diameter measurement just as they came from the test apparatus.

Each value of 'spots per inch', shown on the graphs in this paper, represent the average obtained by counting four to five thousand spots per run. Each value of 'anode spot area', show on these graphs, was obtained by measuring the major and minor diameters of approximately two hundred spots for each run. The number of runs used to determine the curves plotted on the graphs is tabulated in Table I. Again it is emphasized that the curves were constructed from data obtained using anode surfaces whose only preperation was a through cleaning with a carbon tetrachloride scrubbing. Where presented, curves obtained by using anodes surfaces different from above , the curves are so labeled.

DISCUSSION OF RESULTS

The discussion in this section will cover the general findings of the experimental investigations. In particular, the following subjects will be covered in the order indicated:-

(a). Arc parameters controlled, with specific attention to the details and methods employed in controlling these parameters.

(b). The determination of the variation, with arc current and electrode speed, of the arc potential drop.

(c). The existance of a minimum or 'threshold' current whose value is dependant upon the anode material, the anode speed and the anode surface condition.

(d). The general appearance of the anode spot trace, with specific attention to the two major types of variations that occur to disrupt the the appearance of the normally uniform, regular spot trace.

(e). A discussion of the graphs obtained by plotting the number of anode spots formed per inch of anode surface and the graphs obtained by plotting the number of anode spots formed per second.

(f). A description of the appearance of ~~tge~~ the anode spots a viewed through a microscope with the differences between the appearances of the aluminum anode spots and the copper anode spots.

(g). A description of the method used to determine the anode spot areas and a discussion of the graphs obtained by plotting the anode spot areas.

(h). A discussion of the significance of the graphs showing the apparent current densities.

(i). A discussion of the melted anode area obtained per unit time.

(j). A discussion of the apparent surface melting efficiency of the arc.

This section will be concluded with a summary of the more significant points herein covered in detail.

As previously mentioned, the high current, high speed electrode, direct current arc is particularly well suited to the study of phenomena occuring at the anode of the arc. This paper, therefore, is restricted to a discussion of certain phenomena occuring at the anode.

ARC PARAMETERS

During the course of the investigation herein reported, the following arc parameters were controlled:-

(a). CATHODE MATERIAL Carbon cathodes were used exclusively throughout the series of experiments, They were made in the form on 1/4 inch diameter rods, eight inches long. The cathode rods were arc carbons manufactured by the National Carbon Company of Cleveland and San Francisco.

(b). ANODE MATERIAL Commercially pure, cold rolled, copper and aluminum strips, six inches dide and 0.030 inches thick were used. The surface of the anode metals was usually cleaned by scrubbing with carbon tetrachloride, although a few were not so cleaned. A limited number of runs were made with the surface oxide of the copper anode removed by using a dilute hydrochloric acid wash. A few runs were made with the

anode surface roughened slightly by rotating the anode against a steel wire brush. Half of these latter tapes were subsequently cleaned with carbon tetrachloride and the remainder were not. The data presented in this paper is based upon experiments conducted using cleaned unroughened anode surfaces. Where the use of uncleaned or roughened anode surfaces produced significantly different phenomena that fact is noted in the discussion.

(c). ANODE SPEED Speeds from 1,000 to 10,000 feet per minute were employed with the emphasis placed on the speed range from 3,000 to 8,000 feet per minute.

(d). CATHODE SPEEDS Speeds from five to fifty feet per minute were used. It should be noted that the relative speed between the anode and the cathode is the variable plotted in Figures 11. through 37. However, because the cathode speed never exceeded three percent of the anode speed, it is felt that no appreciable differences in the other measured variables would have been detectable had the entire relative speed been produced soley by motion of the anode.

(e). ANODE - CATHODE SEPERATION For all runs conducted during this investigation the electrode seperation was set at 1/8 inch and maintained within five percent of this value. It was deemed advisable to maintain this tolerance because of the variation, with electrode seperation, of the number of anode spots formed per inch, noted by Skolnik[25] in his report of investigations conducted at lower anode speeds.

(f). ARC CURRENT The control of the arc current was only roughly predictable when the current controls of the General Electric, 300 ampere welding generator, used as the arc current power supply, were employed. Normally, the arc current was from twenty five to one hundred amperes less than the value set on the controls. This variation appeared to be dependent upon the magnitude of the arc current, the anode speed and the condition of the surface of the anode. In view of the extremely short time that the arc could be allowed to remain burning, it was deemed impractical to attempt to adjust the arc current to an exact value. However, at all times the Esterline-Angus recording ammeter was used to make a permanent record of the arc current.

(g). ATMOSPHERIC HUMIDITY Because of the variation, with atmospheric humidity, of the arc voltage, for constant values of arc current, reported by Skolnik[25], experimental data was gathered only when the moisture content of the surrounding atmosphere approached 7.56 grains per cubic foot of air. This moisture content corresponds approximately to a relative humidity of eighty percent at a temperture of 75° F. Frequently the required moisture content of the air in the room containing the experimental apparatus could be raised to the desired value by the use of heated evaporating trays. No means were available for decreasing the moisture content of the air except to wait for a change of weather.

ARC POTENTIAL DROP

(a). Method of measurement

Because of the high speed of the anode, it was impracticable to attempt to touch the cathode tip and the portion of the anode surface directly under this tip with probes while the arc was burning. Because the presence of probes in the arc column itself would disturb the normal operation[23] and because of the uncertainty of the exact location of the anode end of the arc[6,7,8,11,25], the floating probe method ~~of~~ of measuring the arc potential drop was also discarded as not feasable. As a practicable method of obtaining rough values of the arc potential drop, for the various anode speeds and arc currents, the recording voltmeter was connected across the cathode receptical and the anode brush rigging. The ohmic resistance of the anode wheel and axle between the section of the anode under the cathode tip and the anode assembly slip rings was measured. The potential drop of the cathode, from its receptical to its tip, was also measured for various values of current. The brush contact potential drop was assumed to be 1.3 volts[24].

(b). Plot of the arc potential drop

After correcting the measured value of the potential drop between the cathode receptical and the anode brush rigging, for the calculated values of the 'IR' drop in the anode wheel assembly and the cathode electrode and after making the estimated correction for brush drop, the variation, with arc current, of the potential drop of the arc was plotted in Figure 11, for various values of anode speed. In this admittedly rough estimate, there is no discernable difference ~~in~~

in the arc potential drop measured for the two anode metals (copper and aluminum) used in these experiments. This result differs from that shown by Spann[26] for stationary bare electrodes of the same metals. Spann indicates a difference in arc potential drop of approximately three percent for the arcs between stationary aluminum electrodes and stationary copper electrodes. Because of the uncertinaty in the actual value of the anode assembly brush potential drop and the unavoidable inaccuracies introduced in the calculation of the heated cathode potential drop, the author estimates that the arc potential drops noted on Figure 11. may be in error by as much as five percent. Therefore if a variation of the same order as found by Spann for the case of the stationary electrodes also exists in the high electrode speed arc, this variation could easily be masked by inaccuracies of the potential drop determination.

(c) Effects of surface condition of the anode

It is to be noted that the data shown in Figure 11. was obtained with clean unroughened anode surfaces. However, a slight roughening of the anode surface by means of a steel wire brush had no noticeable effect on the arc potential drop, whereas, the presence of surface dirt, heavy coating of the anode metal oxide, or carbon deposits, on the anode surface appeared to cause a decrease in the arc potential drop of the order of one to two percent. Because of the difficulties encountered in trying to create uniformly dirty or uniformly coated anode surfaces, reproducable results were not obtainable.

THRESHOLD CURRENT

(a) Previous investigations

Previous investigators of the high current high electrode speed arc had discovered that for each value of anode - cathode seperation, anode speed and electrode material, there appeared to be a minimum or 'threshold' value of arc current dependent on the variables mentioned above. For current values below this 'threshold' the arc either could not be ignited or was not stable.

(b). Methods for determining the 'threshold current'

At the suggestion of Jones[8,11] the author attempted to establish exact values of this 'threshold' current for the range of speeds herein employed and for an electrode seperation of one eighth of an inch. It was determined that the 'threshold' value of the arc current, for any value of anode speed, could be located by three methods.

(1). This 'threshold' value could be found by determining the minimum current required to ignite a stable arc by shorting the anode to the cathode and then removing the shorting instrument from the vicinity of the arc while the anode was traveling at a constant speed.

(2). The 'threshold' value could also be determined by holding the anode speed constant and decreasing the arc current gradually and noting the value of arc current when the arc extinguished.

(3). The third method was to hold the arc current constant and increase the anode speed until the arc extinguished.

All three methods were used to locate the 'threshold' current value for currents up to two hundrde amperes. Methods (2) and (3) gave

identical results, while method (1) usually gave values of three to five amperes less. For currents above two hundred amperes, because of the relatively slow acceleration of the heavy anode wheel and because of the increase, with time, in the distance between the cathode tip and the anode surface, due to the thermal reactions at the cathode, it was impossible to reach the anode speed necessary for extinguishing the arc before the electrode seperation had increased to an unacceptable value. Therefore, for arc currents above two hundred amperes, the methods (1) and (2) were used to determine the value of 'threshold' current. In the case of disagreement between the values obtained by using these two methods, the value obtained by the procedure of reducing the arc current was accepted as the more accurate.

(c). Plot of 'threshold' current for aluminum anode

Figure 12. is a plot of the variation, with anode speed, of the minimum or 'threshold' current for aluminum and copper anodes. It is to be noted that the 'threshold' value for the aluminum anode is greatly effected by the surface condition. The lower curve was obtained by using the aluminum tape just as supplied by the rolling mill, except that it was wiped with a clean dry cloth before each run. This wiping of course did not remove the ever present surface coating of aluminum oxide, nor did it appreciably disturb the thin grease coating placed on the surface during the rolling operation. The upper curve of 'threshold' current was obtained only after the surface dirt had been removed from the aluminum anode by scrubbing with carbon tetrachloride. This cleaning did not remove the aluminum oxide coating from the anode, but it was an effective method of removing the grease

from the surface of the anode. These two curves give a clue as to why an apparently stable arc of three to five amperes less than the 'threshold' current could be initiated by shorting the anode to the cathode by a carbon shorting rod. It appears probable that the rubbing of the shorting rod against the moving anode could grind off some of this carbon shorting rod and if the carbon dust settled on the anode, it would make the anode appear slightly 'dirty', consequently the minimum or 'threshold' current thus determined would tend to approach the value shown on the lower of the curves. Both curves for the aluminum anode appear to approach asymptotically to a constant minimum 'threshold' current of about forty amperes for anode speeds below 1,000 feet per minute, while for anode speeds above 3,000 feet per minute the 'threshold' current increases linearly with anode speed. In the linear portion of the curves the slope of the 'threshold' current for the cleaned aluminum anode is three and one half times the slope of the curve for the 'dirty' aluminum anode.

(d). Plot of 'threshold' current for copper anode

For copper anodes the value of the minimum or 'threshold' current did not appear to be dependent upon the condition of the anode surface. A single smooth curve being obtained from points measured using both types of surfaces (ie. cleaned and uncleaned). At the lower values of anode speeds the 'threshold' value of arc current asymptotically approaches a minimum value of about eighty amperes. This value agrees fairly well with the value obtained by Kouwenhoven, Jones and List[27]. At the higher values of anode speed the minimum value for the arc current increases linearly with anode speed. The slope of

the curve of the 'threshold' current , for the copper anodé, is less than that for the clean aluminmu anode, but it is greater than that for the 'dirty' aluminum anode.

ANODE SPOT TRACE APPEARANCE

(a). General appearance of the low speed anode spot trace

Figure 13. shows a typical view of the anode spots recorded on a copper tape by a stable arc and is representitive of the anode spot traces obtained at the lower values of arc current and anode speeds up to about 4,000 feet per minute. It is to be noted that the distance between spots, in the direction of the trace of the relative motion between the anode and cathode, are fairly uniform. The general appearance of the aluminum anode tapes are very similar, except for the small differences in spot seperation and the differences in the spot size. However, as indicated later, microscopic examination of the individual spots show significant differences in the appearance of these individual spots.

(b). 'Multiple' spot trace

Under certain conditions of anode speed and arc current, the uniformity of the appearance of the spot trace was disturbed in in two different ways, the first of which is discussed herein.

As the speed of the anode was increased above 3,500 to4,000 feet per minute, or when the arc current was increased above about three hundred amperes, the general appearance of the trace of the spots on the copper anode underwent a gradual change. Figures 13, 14 and 15 illustrate this change.

Figure 13. shows that the arc current at the anode probably moved in a regular 'walking' manner along the anode surface. The high speed

motion pictures of the arc, taken by earlier investigators[6,7,8,25] showed that, at the smaller values of anode speed, the arc current at the anode spot actually walked from one point to the next, with the arc extinguishing at the first point simultaneously with its ignition at the next point. Figure 14. shows a few spot 'doublets' with their common axis oriented transverse to the direction of motion of the anode. The question, naturally arises; were these spots formed by the arc 'walking' sidewards, or did the arc stream split and simultaneously anchor at two distinct points? Figure 15. shows the general appearance of the anode spot trace under those conditions of arc current and anode speeds when the anode spot trace was composed almost entirely of spot 'doublets' and 'triplets' oriented with their common axis transverse to the direction of travel of the anode.

Because of the irregularity and the high formation frequency of these spots on the copper anodes it was impossible to directly verify or disprove the simultaneous existance of 'multiple' anode spots, either by means of high speed photographs or oscillagraph studies.

The 'multiple' spots first showed up on the copper anode as occasional, reaccuring doublets oriented transverse to the arc track. As the arc current and the speed of the copper anode was increased, more and more doublets appeared among the closely spaced anode spots. At still higher values of anode speeds and arc current, occasional spot 'triplets' were detectable. At the very high values of arc current and anode speeds, frequent rows of four and five spots, with their common axis transverse to the direction of travel of the anode were detectable. This fact seems to be sufficient evidence to justify the assumption

that more than one anode spot could be formed at a given instant. At a later point in this discussion additional reasons will be advanced to support the authors opinion that these 'multiple' anode spots were probably formed by the arc stream splitting and simultaneously anchoring at two or more distinct spots and were not formed by the arc stream 'walking' sidewards.

In the current and speed range investigated, it was only rarely that the aluminum anodes showed any evidences of multiple spots. These 'multiple' spots on the aluminum anodes occured as one doublet pair among several thousands of distinct seperate spots.

(c). Sinusoidal variations in the recorded anode track

The second disturbance in the regular uniform appearance of the anode spot trace took the following form. Frequently the copper anode spot trace would make laterial deviations from the trace line. These lateral deviations would occasionally take on a regular pattern for short portions of the anode spot track. These deviations, when occuring, appeared to be roughly sinusoidal. A close inspection of the nature of these brief excursions showed that they usually appeared to be formed by the anode spot attempting to superimpose an angular velocity of approximately 2500 revotutions per second on the linear velocity produced by the motion of the anode. In an attempt to find a reason for these deviations, it was found that the welding generator, used as a source for the arc current, had an a.c. component superimposed on the d.c. output voltage. The measured frequency of this a.c. component was 2550 cycles per second and its amplitude was approximately two percent of the d.c. output voltage of the machine. There

were no other a.c. frequencies of significant amplitude detected in the output of the welding generator.

Because of the close correlation between the frequency of the a.c. component of the arc current generator output and the apparent deviation frequency of the anode spots from their mean trace line, it appears feasible to postulate that these excursions were caused by some type of motor action between the arc plasma and the a.c. component of the magnetic field created by the a.c. currents that flow in the anode tape. In particular, the apparent rotational rate of the anode spot trace appears to indicate that the arc plasma might be approaching the rotational rate of the armature of an ideal, single phase, synchorous motor or that of a very low loss induction motor.

At the highest anode speeds, because of the apparent tendency of the arc to form 'multiple' spots, any sinusoidal variations of the anode trace that might have existed were partially obscured by the existance of these 'multiple' spots. At the lowest values of anode speed investigated there were an insufficient number of anode spots formed during the period of one cycle of the a.c. component of the arc current generator output for these lateral deveations to appear to follow a regular pattern.

The formation frequency of the aluminum anode spots was sufficiently lower than that obtained on the copper anodes, and the average diameter of the anode spots was so much larger than those on the copper tapes that any evidences of the lateral deviations that might have existed in the recordéd anode track on the aluminum anode were obscured by these conditions.

NUMBER OF ANODE SPOTS FORMED PER INCH

Figures 16. and 17., for aluminum and copper respectively, show the vaiation, with arc current, in the number of anode spots formed per inch at vavious values of anode speed. Figures 18. and 19. are a replot of the same information using anode speed as the independant variable and the total arc current as the parameter. Figure 16. shows, that for the aluminum anode, the number of spots formed per inch increases with arc current and for a given arc current, a decrease in the number of spots formed per inch can be obtained by an increase in anode speed. On the other hand, Figure 17. shows, that for the copper anode, while the number of spots formed per inch also increases with increasing arc current, for a given value of arc current, an increase in the anode speed will result in an increase in the number of anode spots formed per inch. Figure 18. shows, that for each value of arc current, the number of spots formed per inch, on the aluminum anode, decreases and approaches a minimum asymptotic value for increasing values of anode speed. This asymptotic value seems to increase in an approximately linear fashon with increases in arc current and requires larger values of anode speed to reach the minimum value at the higher values of arc current. Figure 19. shows that the number of spots formed per inch on the copper anode increases and approaches a maximum asymptotic value for each value of arc current. As in case of the aluminum anode, this asymptotic value seems to increase linearly with arc current.

These facts seem to indicate that, for the aluminum anode, the anode end of the arc stream must remain at a given position for a

fixed length of time in order to achieve arc stability. This period appears to depend primarily on the value of total arc current. On the other hand, for a stable arc to exist, the copper anode seems to require that the arc plasma be not extended beyond a fixed maximum length, by the motion of the anode, before reignition takes place.

NUMBER OF ANODE SPOTS FORMED PER SECOND

Figures 20. and 21., for aluminum and copper respectively, show the variation, with arc current, of the number of anode spots formed per second at various values of anode speed. Figures 22. and 23. are a replot of the same data using anode speed as the independant variable and arc current as the parameter. As previously mentioned, for the aluminum anode, all the spots formed seemed to be created individually with very little evidence of the existance of 'multiple' spots. The increase in the number of spots formed per second, with increasing anode speeds, appears to proceed in an orderly fashion as indicated on Figures 20. and 22. However, for the copper anode, at arc currents above three hundred amperes, in the lower range of the anode speeds investigated, and for every value of arc current at anode speeds above 4,000 feet per minute, the increase in the spot formation frequency with an increase in anode speed or arc current was primarly caused by what seemed to be the rapid growth of the tendancy for two or more anode spots to exist concurrently. As previously indicated, a comparison of Figures 13. and 15. show the marked dirrerence in the appearance exibited by the anode trace of the mono-spot arc and the trace of the multi-spot arc. This transition from single spots to 'multiple' spots is evidenced

in the greatly increased slope of the 'spots per second' curve plotted against arc current in the higher range of anode speeds (Figure 21). Its effects may also be seen in the variation of the slopes of the constant current lines plotted on Figure 23. (spots per inch vs anode speed). On this plot it can be seen that, for currents below three hundred amperes, the slope of the constant current lines decreases with an increase in anode speed, while for currents above this value, the slope increases with an increase in anode speed.

MICROSCOPIC EXAMINATION OF THE ANODE SPOTS

(a). Photographs of the anode spots

As previously indicated, Figures 13. through 15. show the general appearance of the arc traces on the anode surface. Figure 13. is typical of the appearance of all aluminum anode spot traces and also of the low anode speed copper anode spot traces. Figure 14. and Figure 15. are typical of the high speed copper anode spot traces. Figures 4. through 10. show magnified views of spots for different types of anode material, different values of arc current and different values of anode speed. To permit the proper visualization of the size of these spots, a scale has been superimposed on these latter Figures. Each major division of this scale represents a measurement of one sixth millimeter on the anode surface.

(b). The aluminum anode spots

The views of the spots formed on the aluminum anodes (Figures 4. to 6.) show four distinct identifiable regions, namely:-

(1). A central portion that has the appearance of a circular

mound that seems to approach a relatively sharp point (Figure 5.) surrounded by a slight depression or 'moat'. Figure 4. shows the same characteristic mound, except that in this Figure it appears as though the mound tip had collapsed to form a slight crater. Figure 6. gives evidence that a mound had existed but the collapse of the central region was sufficiently extensive to practically obliterate the mound. In all instances, the mound and its surrounding 'moat' were colored a deep blue, as though the metal had been heated above the melting point and then quenched suddenly.

(2). The next region is annular in shape and surrounds the 'moat'. It has a sharply defined outer circumference and a slightly 'furrowed' surface. The 'furrows' are particularly evident in Figure 5., but they may also be seen in Figures 4. and 6.

(3). The third region is also annular and encompasses the two regions previously described. Its surface is relatively bright and usually free from surface discolorations. This region may most easily be seen in Figures 4. and 5.

(4). The last distinctive region is a hazy ring around the spot and appears to be composed of a thick layer of aluminum oxide and a heavy coating of carbon surface deposits.

All the aluminum spots examined were composed of the four distinct regions outlined above. The relative proportion of the areas of each region changed with changes of arc current and anode speed. For low values of arc current the inner area had a definate mound with a 'collapsed' tip and the moat surrounding the mound was well defined.

The best means of locating the limits of this region was its characteristic deep blue color. With an increase in arc current the mound area increased more rapidly than the other areas, thereby tending to obscure the other distinguishable areas. Figure 6. shows the mound area occupying practically the entire spot area and only very small portions of the other distinct areas visable.

(i). Rotation of the melted aluminum anode metal

No rotational motion, or vorticity, was evident in the mound area, however the furrowed section was invariably grooved in such a direction as to suggest possible rotational motion of the metal. The furrows, as shown by Figures 4. and 5., were along lines that appeared to be rotated counter-clockwise with respect to the radii extending from the center of the spot.

(ii). Effects of the aluminum anode surface condition of the spot appearance

The only material difference that could be distinguished among the spots made on the aluminum anodes with different surface conditions was in the size of the outermost characteristic area. This hazy, darkly colored, area was much larger for those anode tapes whose surfaces had originally been roughened by means of a steel wire brush, or whose surface dirt had not been removed, than were the corresponding areas produced on aluminum tapes whose surfaces had been cleaned with carbon tetrachloride.

(c). The copper anode spots

As seen in Figures 7. through 10. there were only two distinguishable regions in the anode spots formed on copper tapes. The surface coating of carbon deposits and copper oxide was approximately circular in shape. In the center of these deposits a small portion of the copper had melted and formed a tiny mound. Surrounding this mound was a usually sharply defined moat, although at the higher values of anode speed the mound with its moat usually had insufficient height and depth contrast to permit easy identification. Figures 7. and 8. show how clearly the anode spots, on copper tapes, are defined after the surrounding coating of surface deposited carbon has been removed by means of a dilute hydrochloric acid bath.

(i). Rotation of the melted copper anode metal

Close inspection of Figure 10. shows the existance of circular 'contour' lines around the copper mound. In a few of the thousands of spots examined it was possible to follow a single 'contour' line as it circled the mound two or three times. In all such cases the line spiraled in a counter-clockwise direction as the line was traced from the base towards the tip of the mound, indicating a possible counter-clockwise rotation of the molten copper.

(ii). Effects of copper anode surface condition on the spot appearance

Figure 10-a. shows the appearance of a typical anode spot formed on a copper tape whose surface had a heavy coating of surface oxide which had not been precleaned prior to the run. There is

little or no evidence of any tendancy for the copper to become sufficiently hot to melt and attempt to form a pip. Although the values of arc current and anode speed used to obtain the spots illustrated in Figures 10. and 10-a. were identical, there is little similarity between the appearance of these spots other than the layer of deposited carbon particles. In the range of arc currents and anode speeds investigated, only at the lowest values of anode speed did a mound develope on a copper anode that had not previously had its surface dirt removed by some cleaning method.

ANODE SPOT AREAS

(a) Area determination

In determining the melted area of the anode spots the major and minor diameters of the outer edges of the 'moat' formed around the copper spots were measured. In the case of the aluminum spots the outermost major and minor diameters of the 'furrowed' areas were measured. The 'melted area was then calculated by assuming that the spots were elliptical in shape.

(b). Plots of the aluminum anode spot areas

Figures 24. and 25. show, for aluminum and copper respectively, the variation, with arc current, of the average anode spot area at selected values of anode speed. Figures 26. and 27. are a replot of the same data for constant values of arc current and various values of anode speed. Figure 24. shows, that for anode speeds below a value of 7,000 feet per minute, the aluminum anode spot area increased approximately linearly with arc current. For an anode speed of 7,000 feet

per minute no appreciable change in the aluminum anode spot area was detectable as the current was varied. Over the limited range of arc current values investigated, the anode spot areas formed on an aluminum anode traveling at 8,000 feet per minute appeared to decrease with an increase in arc current. From Figure 24. it is to be noted, that at an anode speed of 3,165 feet per minute for the aluminum anode, while the individual anode spot areas increased linearly with an increase in arc current until a current of about 240 amperes was reached, at the greater values of arc current, this linear relationship was lost. In fact, for arc currents between 280 and 330 amperes the slope of the plot of anode spot area vs arc current is negitive instead of positive. To a lesser extent, this tendancy of the anode spot area to decrease with increases in current, at the larger values of arc current, was also noted for the copper anode as pointed out below.

(c). Plots of the copper anode spot areas

Figure 25. is a plot of the copper anode average spot area, for constant values of anode speed, vs arc current. The appearance of this plot is very similar to that of Figure 24. which shows the same data for aluminum anodes. However the following important differences are to be noted:-

(i). The areas of the copper anode spots are much less than the corresponding aluminum spots formed under identical conditions of anode speed and arc current.

(ii). The copper anode spot area appears to become approximately constant for all values of arc current at an anode speed of

about 5,000 feet per minute as compared with a value of 7,000 feet per minute for the aluminum anode.

(iii). The change in slope in the plot of spot areas evident at an anode speed of 3,165 feet per minute for the aluminum anode, appears to be repeated in the case of the copper anode for anode speeds of 3,165 - 5,000 and 7,000 feet per minute. However it occurs at a higher value of arc current and is much less pronounced.

At the higher values of anode speed and for the larger values of arc current the decrease in the individual copper anode spot areas, with increasing current, appears reasonable if the proposition of simultaneously formed 'multiple' anode spots, previously discussed, is accepted. However the lack of any other evidence of the existance of these 'multiple' spots on the aluminum anode makes the decreasing spot area, with increasing arc current, difficult to explain.

Figure 27. showing the variation, with anode speed, of the copper anode spot area indicates that at an anode speed of approximately 5,000 feet per minute the constant current curves pass through a common point. A comparison with Figure 26. relating to the aluminum anode, shows that the constant curves tend to approach a similar common point at an anode speed of about 7,000 feet per minute. If investigations were to be conducted at much larger values of arc current then were feasible with the equipment used in these experiments, the existance of this common intersection for the aluminum anode might be definatly established.

(d). Limitations in determining spot areas

Although the anode spots formed at the higher values of

anode speed are very regular in appearance and every effort was made to measure the actual maximum and minimum diameters, it is felt that the area determination for the extremely small copper spots encountered at the highest values of anode speed may be in error by as much as ten percent. This percentage error would arise by uncertainties of the order of 1/120 millimeters in the measurement of the major and minor diameters of the smallest copper anode spots. Because they were so much lagger, the same uncertainties in the diameter measurements of the aluminum anode spots would only give rise to errors of about two percent in the spot area determination.

APPARENT CURRENT DENSITY

Figures 28. through 31. are plots of the apparent current density of the arc current entering the anode. These graphs were obtained by dividing the arc current by the calculated average area of the anode spots. Figures 29. and 31. are particularly interesting. They show the variation of the apparent current density of the arc current at the copper anode, Figure 29. shows, that for speeds above 3,165 feet per minute, the curves of constant anode speed when extended below the 'threshold' current, tend to intersect at a common current density of about 115,000 amperes per square centimeter, and an arc current of approximately 180 amperes. Figure 31. shows a much sharper intersection of the constant current lines at an anode speed of 4,000 feet per minute and an apparent current density of 112,000 amperes per square centimeter. These definate intersections and the presence of what appears to be definite multi-coexistant anode spots on the copper tapes,

at certain combinations of anode speed and arc current, seem to be fairly conclusive evidence that, for the particular conditions under which these experiments were conducted, the actual maximum current density that can be supported by a stable arc and a copper anode is very close to 112,000 amperes per square centimeter. The author is of the opinion that the apparent current densities greater than 112,000 amperes per square centimeter, plotted for anode speeds above 4,000 feet per minute, were caused by the erroneous assumption that only a single anode spot existed at any given instant, whereas the appearance of the anode traces at speeds above 4,000 feet per minute, as shown in Figures 14. and 15. seem to contradict this assumption.

If the postulate, that the copper anode will not support, by means of a stable arc, an arc current density greater than 112,000 amperes per square centimeter, at the anode, is true, then some additional reason must be advance to explain the apparent current densities greater than 112,000 amperes per square centimeter (Figures 29. and 31) calculated for the lower values of anode speed and arc current.

Figures 28. and 30. showing the variation, with arc current and anode speed respectively, of the apparent current density at the aluminum anode seem to indicate that investigations at greatly increased values of arc current and / or anode speed must be undertaken to locate the ultimate stable arc current density that can be supported at an aluminum anode, if such an ultimate value exists. Because the trend of the curves of Figure 30. are similar to the trend of the lower current values of Figure 31. it seems logical to suppose that such an ultimate value may exist for the aluminum anode.

TOTAL MELTED AREA PER SECOND

Figures 32. through 35. show the variation, with arc current and anode speed, of the total anode surface area melted per second, for aluminum and copper anodes. These graphs were obtained by multiplying the value of 'anode spots formed per second' (Figures 20. to 23.) with the value of 'anode spot area' (Figures 24. to 27.), for selected values of arc current and anode speed. Figure 32., for aluminum, shows that the total melted area increases in a roughly linear fashion with increases in arc current, and for a given value of arc current, the total melted area is greater for the larger values of anode speed. However, at the higher values of anode speed the slopes of the constant anode speed curves decreases for increasing values of anode speed as shown by Figure 32. (total melted area per second vs anode speed). These changes in the slopes of the constant anode speed curves plotted on Figure 32. make the constant current curves (Figure 34.) appear to approach an asymptotic value for each value of arc current. These curves indicate that the maximum total area that can be melted by a given arc current is obtained when the current is at, or close to the threshold value for a particular value of anode speed.

Figure 33. showing the variation, with arc current, of the total area melted per second, and Figure 35. showing this variation with anode speed, for the copper anode, indicates the marked difference in the total melted area per second for the various values of arc current and anode speed. The differences between these curves and the similar plots for the aluminum anodes (Figures 32. and 34.) and the lack of a uniform pattern of variation with changes in anode speed and arc current,

are apparently caused, either by the unknown factors created by the formation of the 'multiple' spots on the copper anode surfaces, or are the results of inaccuracies in the measurements of the very small copper anode spot areas. However, corrections for the estimated maximum error of plus or minus ten percent, in the area determination of the very small copper anode copper anode spots, would be insufficient to materially alter the shapes of the curves shown on Figures 33. and 35. Therefore it is beleived that these curves give a true representation of the pattern of variation, with anode speed and arc current, of the total copper anode area melted per second.

TOTAL ANODE SURFACE AREA MELTED PER AMPERE PER SECOND

A plot of the variation, with arc current, of the total anode surface area melted per ampere per second can be interpreted as a measure of the efficiency of the arc in transferring energy to the anode surface. The term 'efficiency' used herein is applied in the sense given above.

Figures 36. and 37. show, for aluminum and copper anodes respectively, the variation, with arc current, of the total anode surface area melted per ampere per second at selected values of anode speed. Figure 36. shows, for the aluminum anodes, the efficiency of the arc increases with an increase in arc current for the lower values of arc currents and anode speeds. However, for the large values of arc current, the efficiency appears to decrease with increasing current. This tendency is particularly evident in the plot for an anode speed of 3,165 feet per minute, but it may also be detected in the plot for

the anode speeds of 7,000 and 8,000 feet per minute. This Figure also shows that the melting effeciency, for a given value of arc current, can be increased by an increase in anode speed. For any particular value of anode speed the most efficient utilisation of the arc, for melting the anode surface, occurs when the arc current is maintained at the 'threshold' value for the particular value of anode speed.

Figure 37. shows a similar plot for the copper anode. Here again, the appearance of the 'multiple' anode spots introduces a factor into the calculations for these curves which make it difficult to draw any general conclusions concerning the melting efficiency of the arc between a carbon cathode and a moving copper anode. However there is a very slight similarity between Figures 36. and 37. that can be noticed. In both figures the melting efficiency of the arc increases with an increase in arc current at the lower values of anode speed, and decreases with increases in arc current for the higher values of anode speed.

SUMMARY

The results of the investigations discussed in this paper may be summarized as follows:-

(a). The method of investigating phenomena at the anode of an electric arc between moving electrodes has been extended to encompass anode speeds approaching 10,000 feet per minute.

(b). The existence of a 'threshold' or minimum required value of arc current for the formation of a stable arc between moving electrodes has been verified.

(c). The variation, with anode speed, of this 'threshold' arc current has been measured and found to be different for the cases of moving aluminum and copper anodes at a fixed separation of 1/8 inch from a carbon cathode. The 'threshold' current increases linearly with anode speed, at speeds above 5,000 feet per minute and is higher for copper anodes than for aluminum anodes. For speeds below 5,000 feet per minute the copper anode 'threshold' current asymptotically approaches a value of about 60 amperes, while the aluminum anode 'threshold' asymptotically approaches a value of about 40 amperes.

(d). The dependence upon surface condition of this variation, with anode speed, of the 'threshold' current for aluminum and copper anodes has been noted and roughly measured, showing that a thin grease coating on the copper anode had no measurable effect on the value of 'threshold' current. However, although

the same thin grease coating on the aluminum anode also had negligable effects at speeds below 2,000 feet per minute, it lowered the 'threshold' current appreciably for anode speeds above 3,000 feet per minute.

(e). The probable regular formation of multiple concurrently existing anode spots on copper anodes was detected at all values of arc current, for anode speeds of 5,000 feet per minute and greater, and for arc currents of 300 amperes or greater at anode speeds as low as 3,000 feet per minute.

(f). It was determined that the maximum apparent current density that a copper anode ~~appears to be~~ is able to support, by means of a stable arc, is approximately 100,000 amperes per square centimeter.

(g). For aluminum anodes, apparent current densities of the order of 60,000 amperes per square centimeter were noted, but this value does not appear to be the maximum value that can be supported by means of a stable arc.

(h). For both aluminum and copper anodes, apparent rotational motion in a counter-clockwise direction, of the melted metal in the anode spot was noted over the entire range of anode speeds and arc currents investigated.

(i). For aluminum anodes an unexplained decrease, with increasing arc current, in the individual anode spot areas, the total anode surface area melted per second and the apparent melting efficiency of the arc, was noted for arc currents above 280 amperes and an anode speed of 3,165 feet per minute.

(j). For aluminum anodes traveling at 7,000 feet per minute, increasing the arc current had no effect on the anode spot areas and at anode speeds of 8,000 feet per minute, increases in arc current appeared to cause a decrease in the anode spot areas. Similarly for copper anodes, speeds of 5,000 feet per minute appeared to prevent any changes in the anode spot areas with change in arc current, while speeds above 5,000 feet per minute, the anode spot areas decreased with increases in arc current.

(k). It was noted that, at speeds above 3,000 feet per minute, the copper anode would not melt and form a raised anode spot, if the anode surface was covered with a relatively heavy coating of copper oxide and a thin coating of grease.

LIST OF TABLES AND ILLUSTRATIONS

Figure 28. Variation, with arc current, of the 'Anode spot apparent current density' at selected values of anode speed. Aluminum anode.

Figure 29. Variation, with arc current of the ' Anode spot apparent current density' at selected values of anode speed. Copper anode.

Figure 30. Variation, with anode speed, of the ' Anode spot apparent current density' at selected values of arc current. aluminum anode.

Figure 31. Variation, with anode speed, of the ' Anode spot apparent current density' at selected values of arc current. Copper anode.

Figure 32. Variation, with arc current, of 'Total anode surface area melted per second' at selected values of anode speed. Aluminum anode.

Figure 33. Variation, with arc current, of ' Total anode surface area melted per second' at selected values of anode speed. Copper anode.

Figure 24. Variation, with anode speed, of 'Total anode surface area melted per second' at selected values of arc current. Aluminum anode.

Figure 35. Variation, with anode speed, of 'Total anode surface area melted per second' at selected values of arc current. Copper anode.

Figure 36. Variation, with arc current, of 'Total anode surface area melted per ampere per second' at selected values of anode speed. Aluminum anode.

Figure 37. Variation, with arc current, of 'Total anode surface area melted per ampere per second' at selected values of anode speed. Copper anode.

Table I EXPERIMENTAL RUNS CONDUCTED

TABLE I

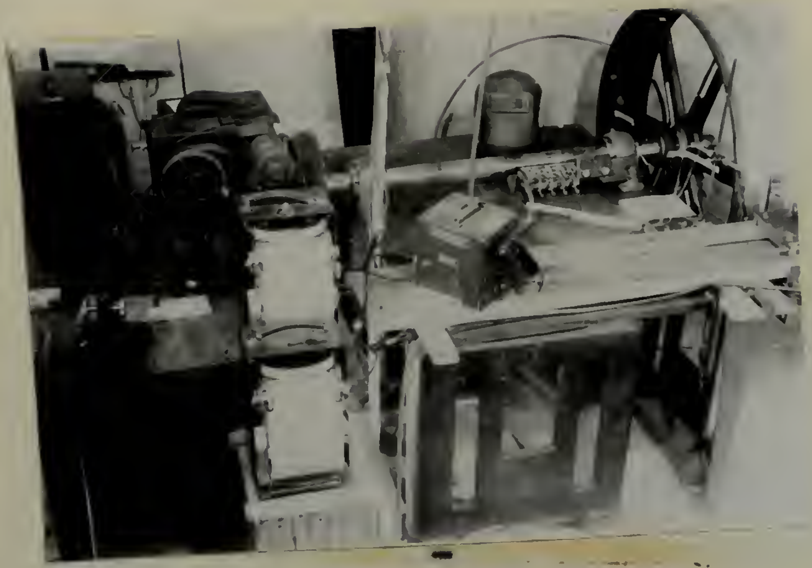
EXPERIMENTAL RUNS CONDUCTED

ANODE METAL	ANODE SPEED FT/MIN	ARC CURRENT	NUMBER OF RUNS	REMARKS
Aluminum (grease coated)	1,000 to 8,000	40 to 150	26	Threshold current determination
Aluminum (clean)	1,000 to 8,000	40 to 300	18	same
Copper (grease coated)	1,000 to 8,000	80 to 300	15	same
Copper (clean)	1,000 to 8,000	80 to 300	15	same
Aluminum (clean)	1,000	80 to 200	5	Approximately 25 ampere steps.
Aluminum (clean)	2,000	80 to 200	5[a]	same
Copper (clean)	2,000	80 to 200	5[a]	same
Aluminum (clean)	3,165	80 to 330	13[a,b]	Approximately 20 ampere steps
Copper (clean)	3,165	135 to 340	9[a,b]	same
Aluminum (clean)	5,000	150 to 220	7[b]	20 ampere steps (repeated)
Copper (clean)	5,000	200 to 340	8[b]	Approximately 20 ampere steps
Aluminum (clean)	7,000	220 to 300	9[a]	Approximately 10 ampere steps
Copper (clean)	7,000	250 to 340	6[a]	Approximately 15 ampere steps
Aluminum (clean)	8,000	300 to 340	4	Two at each end.
Copper	8,000	300 to 320	4	Two at each end.

Superscript 'a' indicates one run conducted with uncleaned surface.

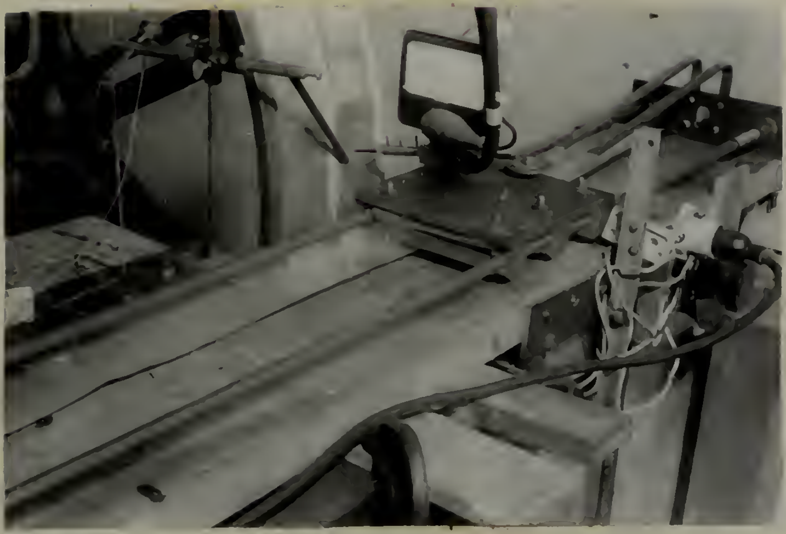
Superscript 'b' indicates one run conducted with 'roughened' surface.

Figure 1.



General view of the high anode speed direct current test apparatus.

Figure 2.



View of the anode wheel and the cathode mounting.

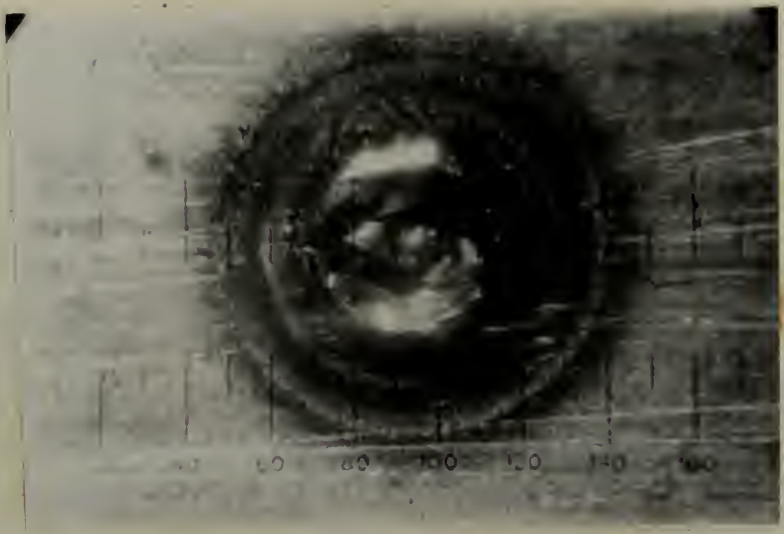
The arc shorting rod is shown in position for

starting the arc.

Figure 3.

View of an ajode tape mounted on the anode wheel showing the partitioning accomplished by insulating tapes.

Figure 4.



Characteristic anode spot formed on an aluminum anode.

Anode speed - 3,165 ft./min., current 105 amps.

Scale:- 1 inch to 0.85 millimeters

Figure 5.

Characteristic anode spot formed on aluminum tape.

Anode speed - 3,165 ft./min., current 205 amps.

Scale:- 1 inch to 0.85 millimeters

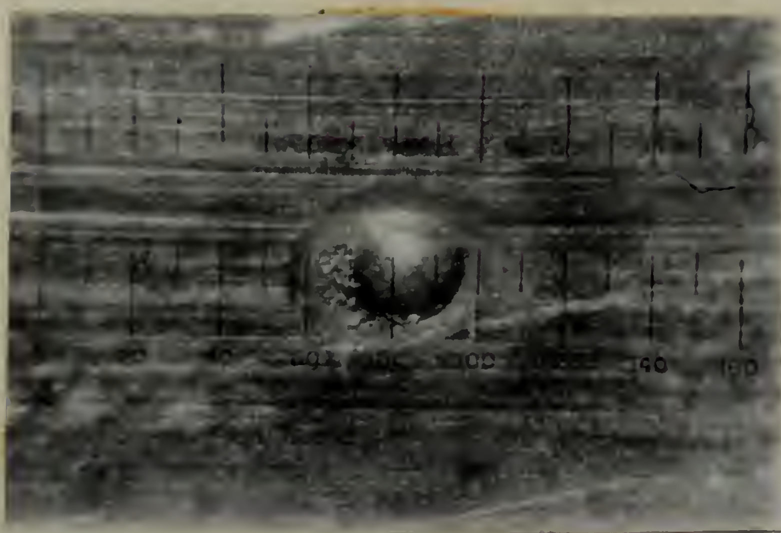
Figure 6.

Characteristic anode spot formed on aluminum tape.

Anode speed - 3,165 ft./min., current 295 amps.

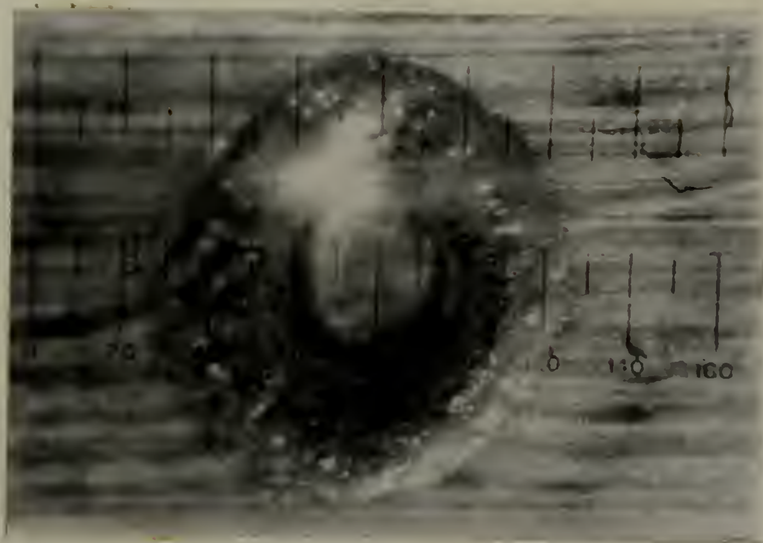
Scale:- 1 inch to 0.85 millimeters.

Figure 7.



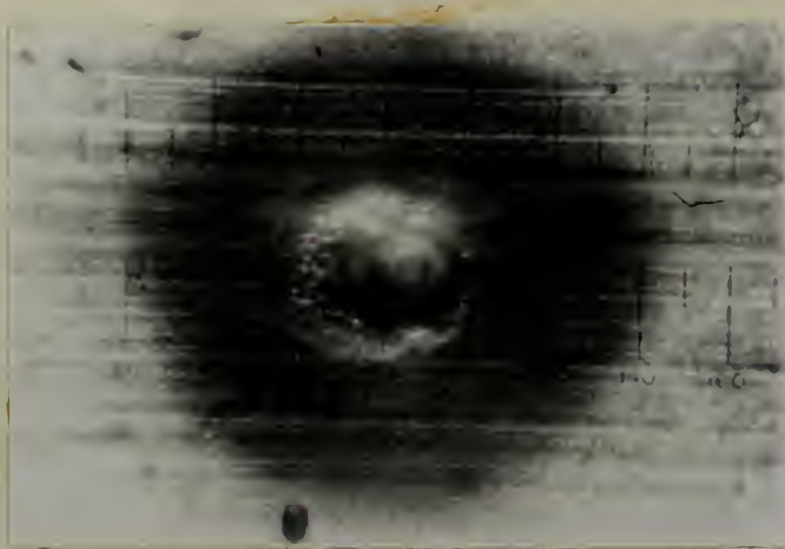
Characteristic anode spot formed on copper tape,
after hydrochloric acid wash removed carbon deposits.
Anode speed - 3,165 ft./min., currett 140 amps.
Scale:- 1 inch to 0.85 millimeters.

Figure 8.



Characteristic anode spot formed on copper anode, after hydrochloric acid wash removed carbon deposits. Anode speed - 3,165 ft./min., current 300 amps. Scale:- 1 inch to 0.85 millimeters.

Figure 9.

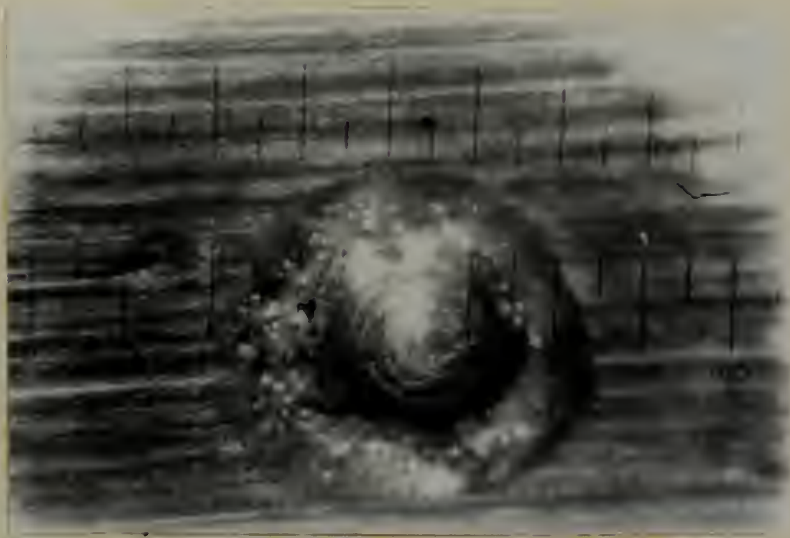


Characteristic anode spot formed on copper tape.

Anode speed - 3,165 ft./min., current 140 amps.

Scale:- 1 inch to 0.85 millimeters.

Figure 10



Characteristec anode spot formed on copper tape.

Anode speed - 3,165 ft./min., current 330 amps.

Scale:- 1 inch to 0.85 millimeters.

Figure 10-a

Characteristic anode spot formed on 'dirty' copper tape.

Anode speed - 3,165 ft./min., current 330 amps.

Scale:- 1 inch to 0.65 millimeters

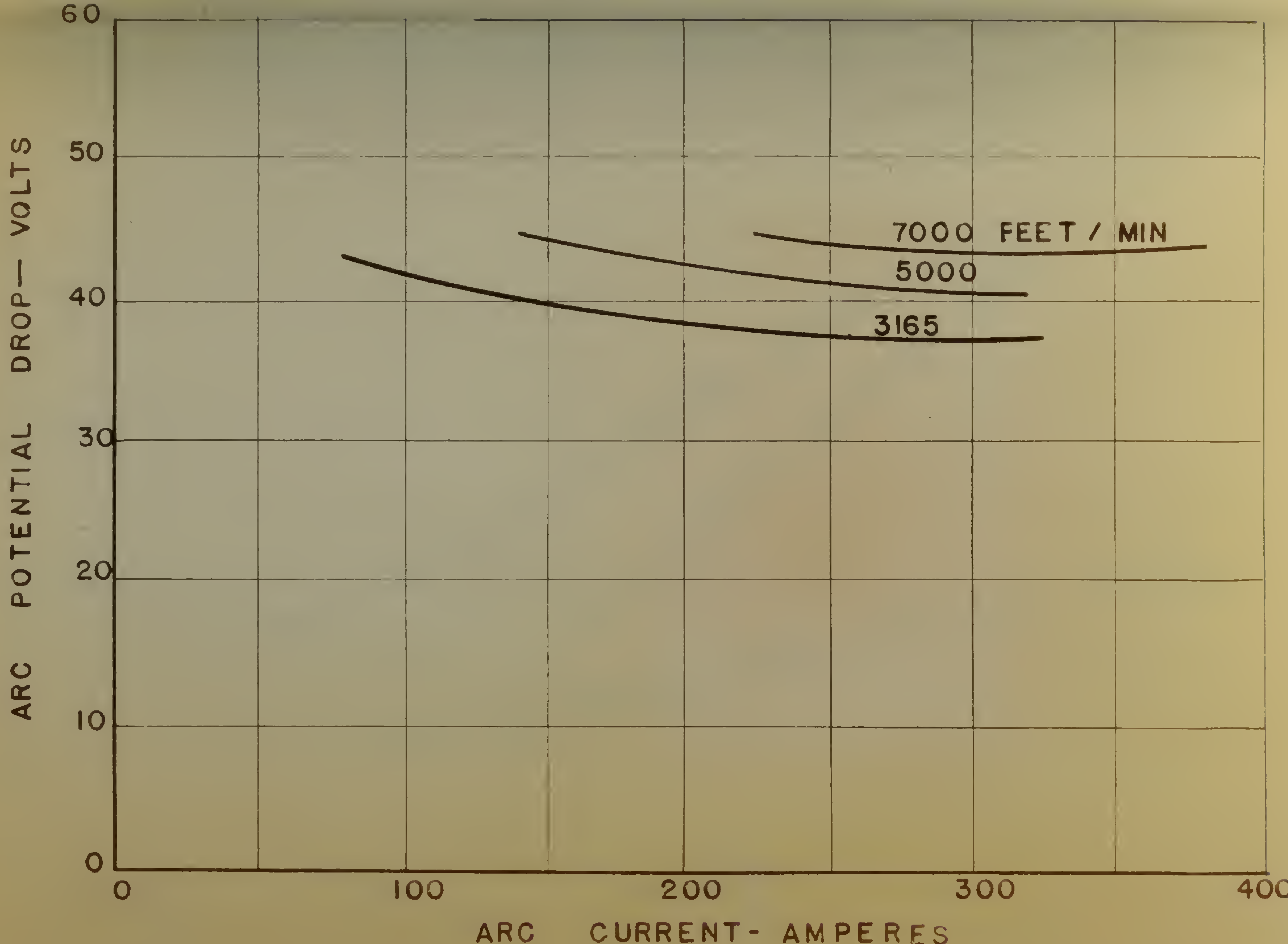


FIGURE. II VARIATION OF ARC POTENTIAL DROP WITH ARC CURRENT FOR ALUMINUM AND COPPER ANODES

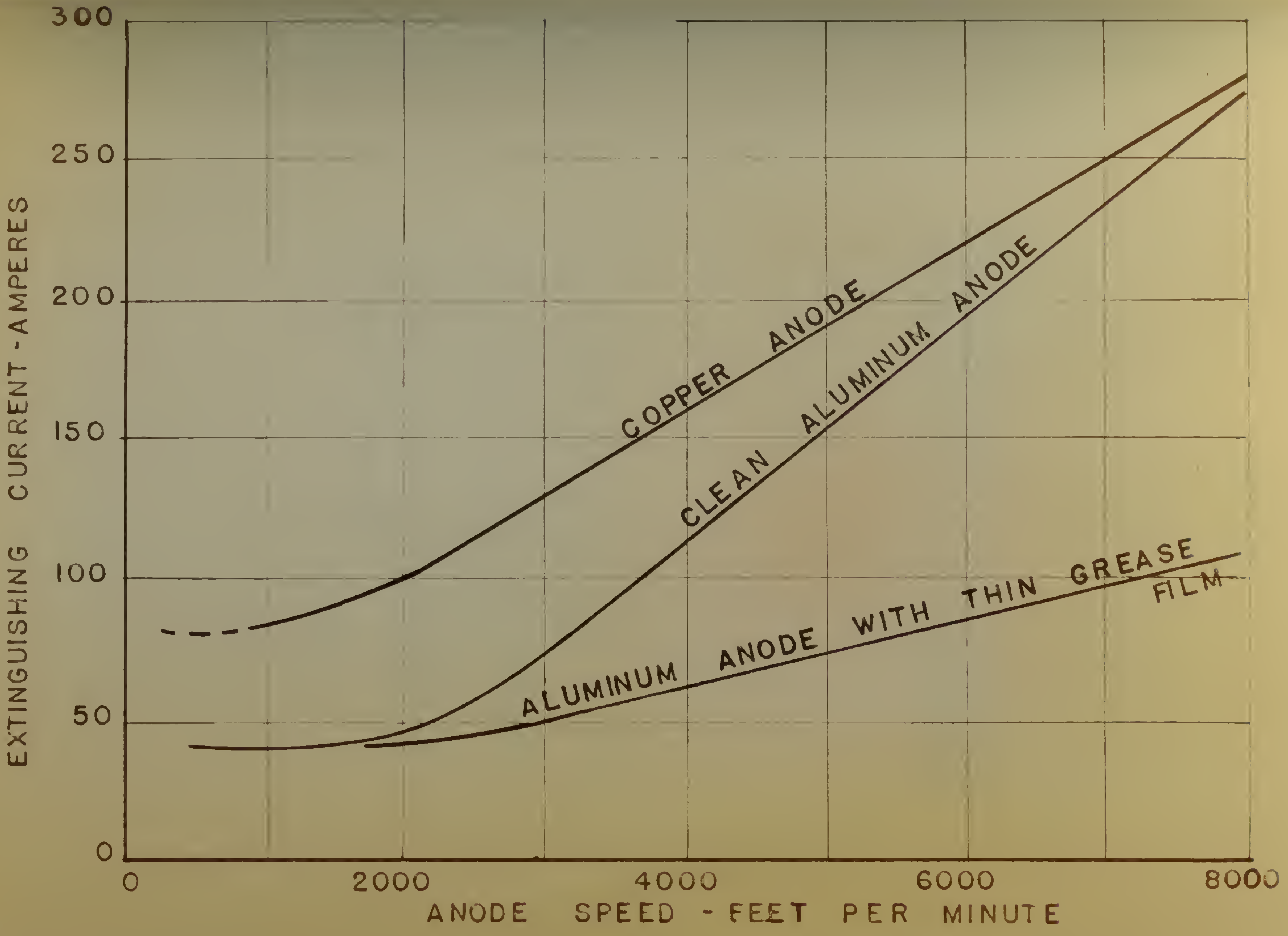


FIGURE 12 VARIATION OF EXTINGUISHING CURRENT WITH ELECTRODE SPEED FOR ALUMINUM ANODE AND COPPER ANODE

Figure 13.

View of typical trace of anode spots on copper tape for low values of anode speed.

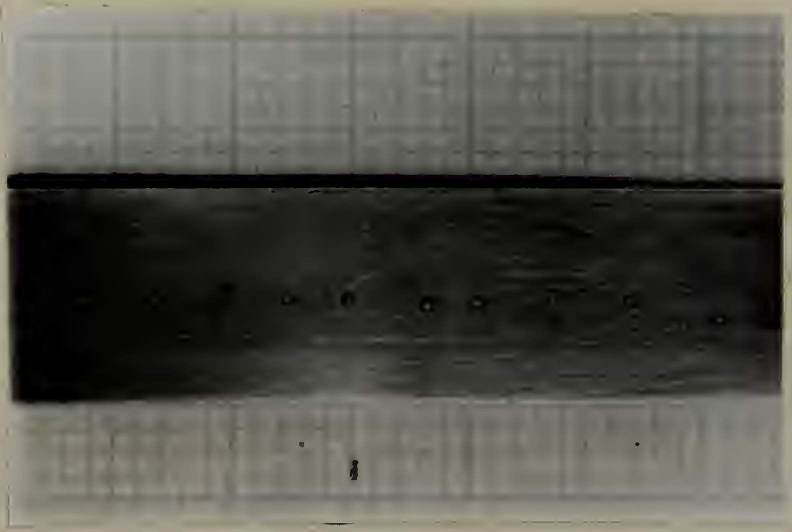
Anode speed 3,165 ft./min., current 140 amps.

~~Scale:- 1 inch to 0.85 millimeters~~

(Note:-Aluminum anode traces are similar for all values of anode speed.)

Scale:- 1 inch to 4 inches.

Figure 14.



View of typical trace of anode spots on copper tape showing slight evidences of 'multiple' spots. Anodes speed:- 5,000 ft./min., currént 200 amps. Scale:- 1 inch to 2 inches.

Figure 15

View of typical trace of anode spots on copper tape, showing definate evidences of 'multiple' spots. Anode speed:- 8,000 ft./min., current 320 amperes.

Scale:- 1 inch to 2 inches.

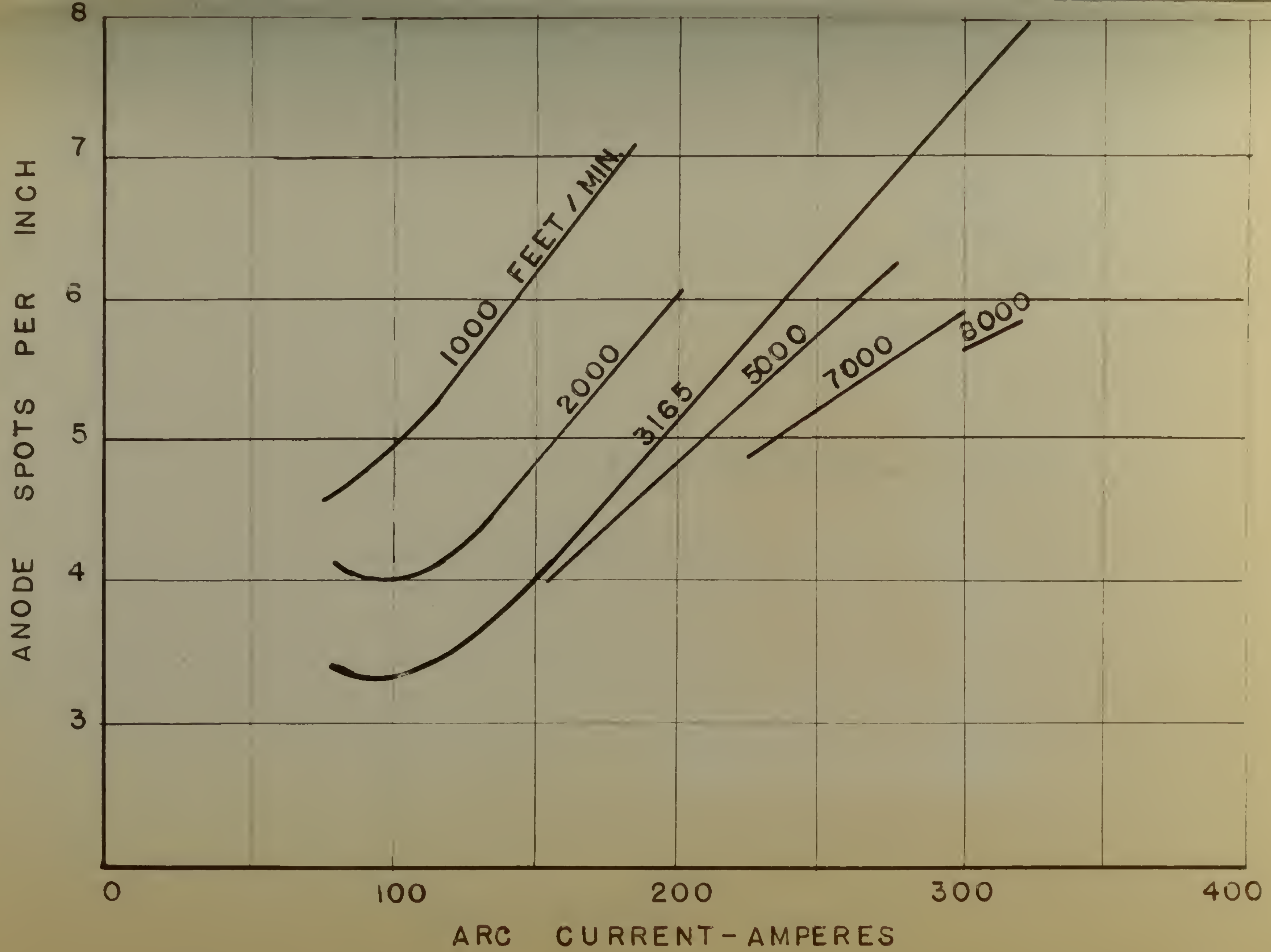


FIGURE 16 VARIATION OF ANODE SPOTS PER INCH WITH ARC CURRENT FOR ALUMINUM ANODE

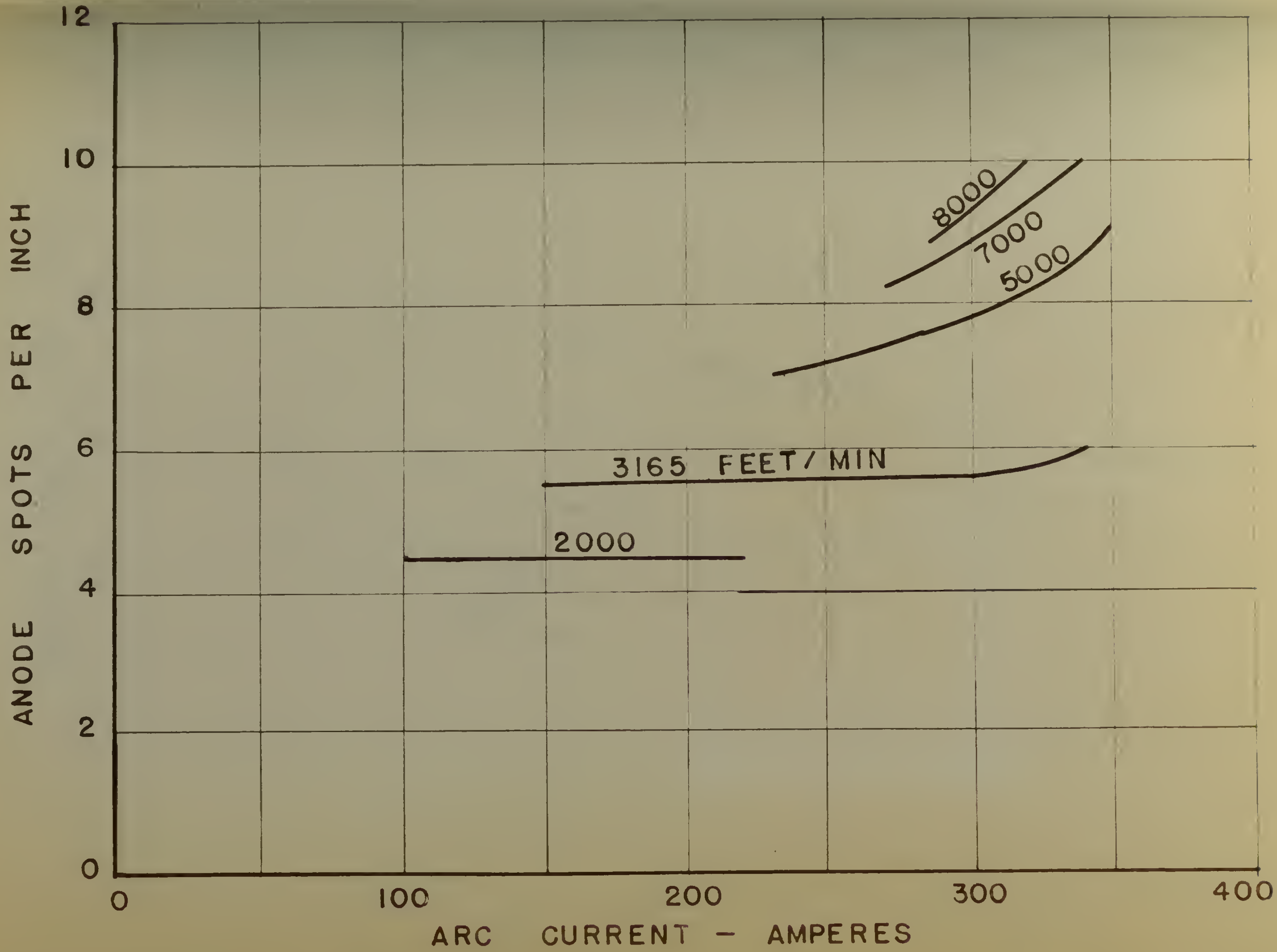


FIGURE 17 VARIATION OF ANODE SPOTS PER INCH WITH ARC CURRENT FOR COPPER ANODE

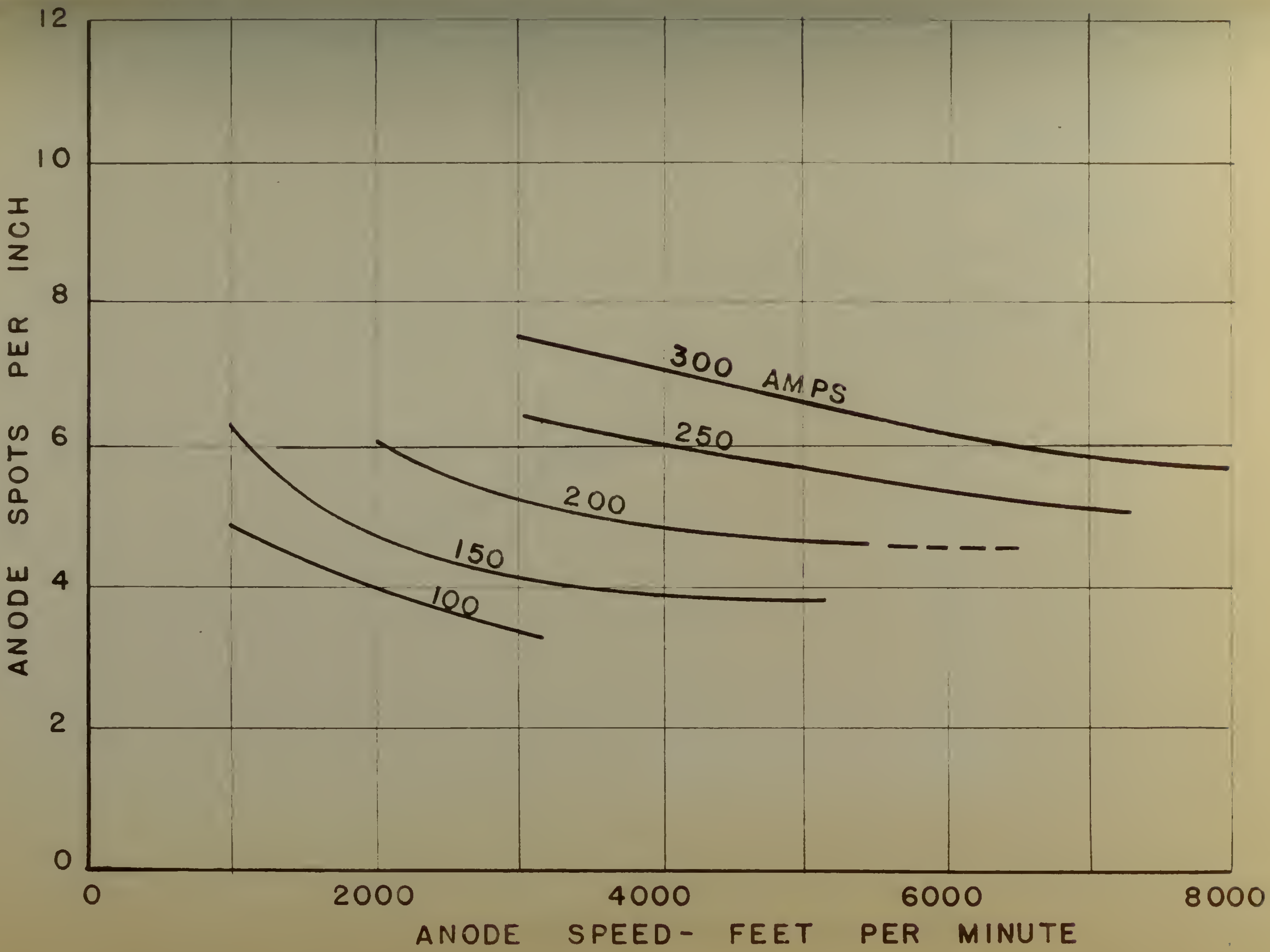


FIGURE 18 VARIATION OF ANODE SPOTS PER INCH WITH ELECTRODE SPEED FOR ALUMINUM ANODE

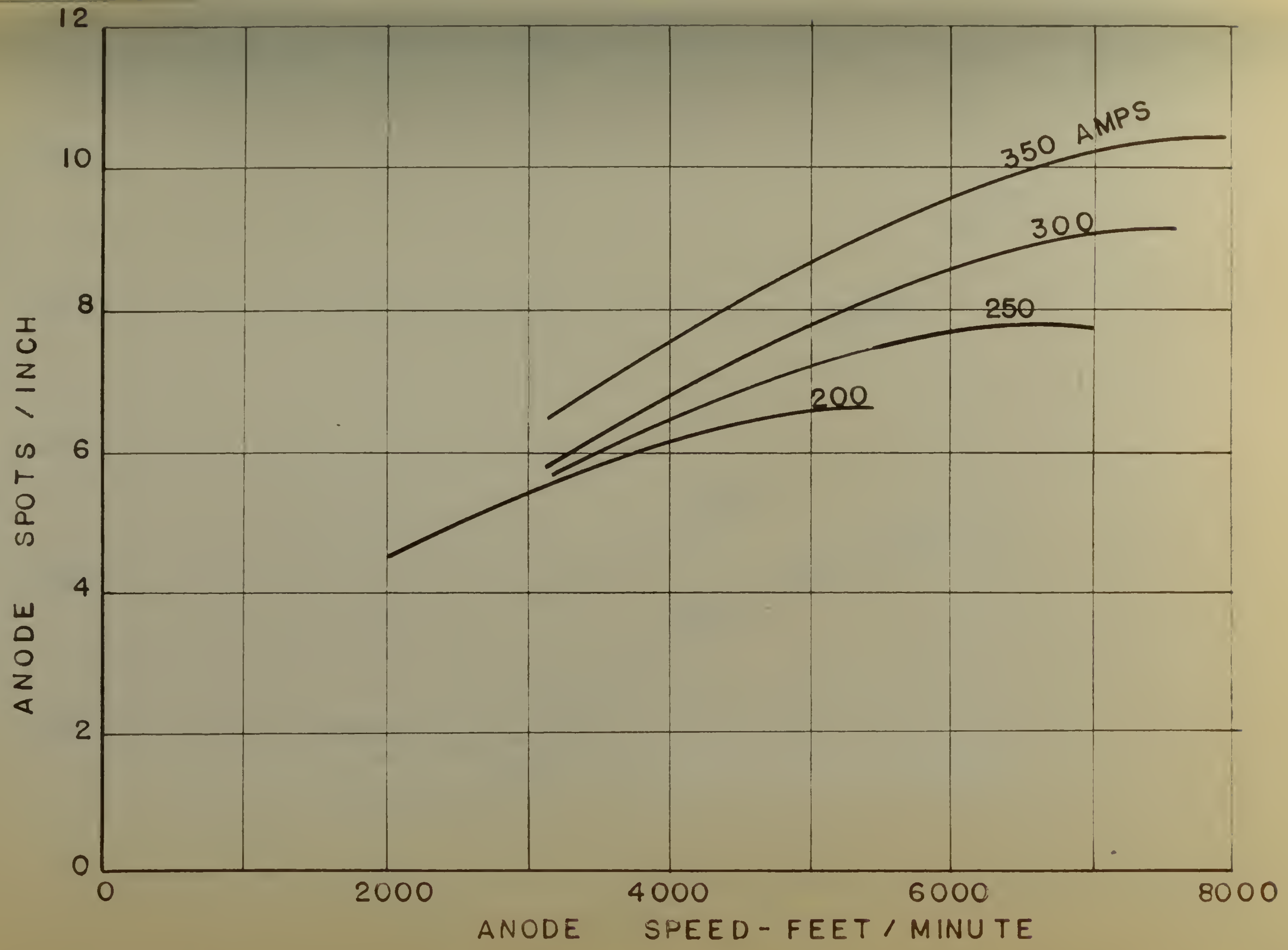


FIGURE 19 VARIATION OF ANODE SPOTS PER INCH WITH ANODE SPEED FOR COPPER ANODE

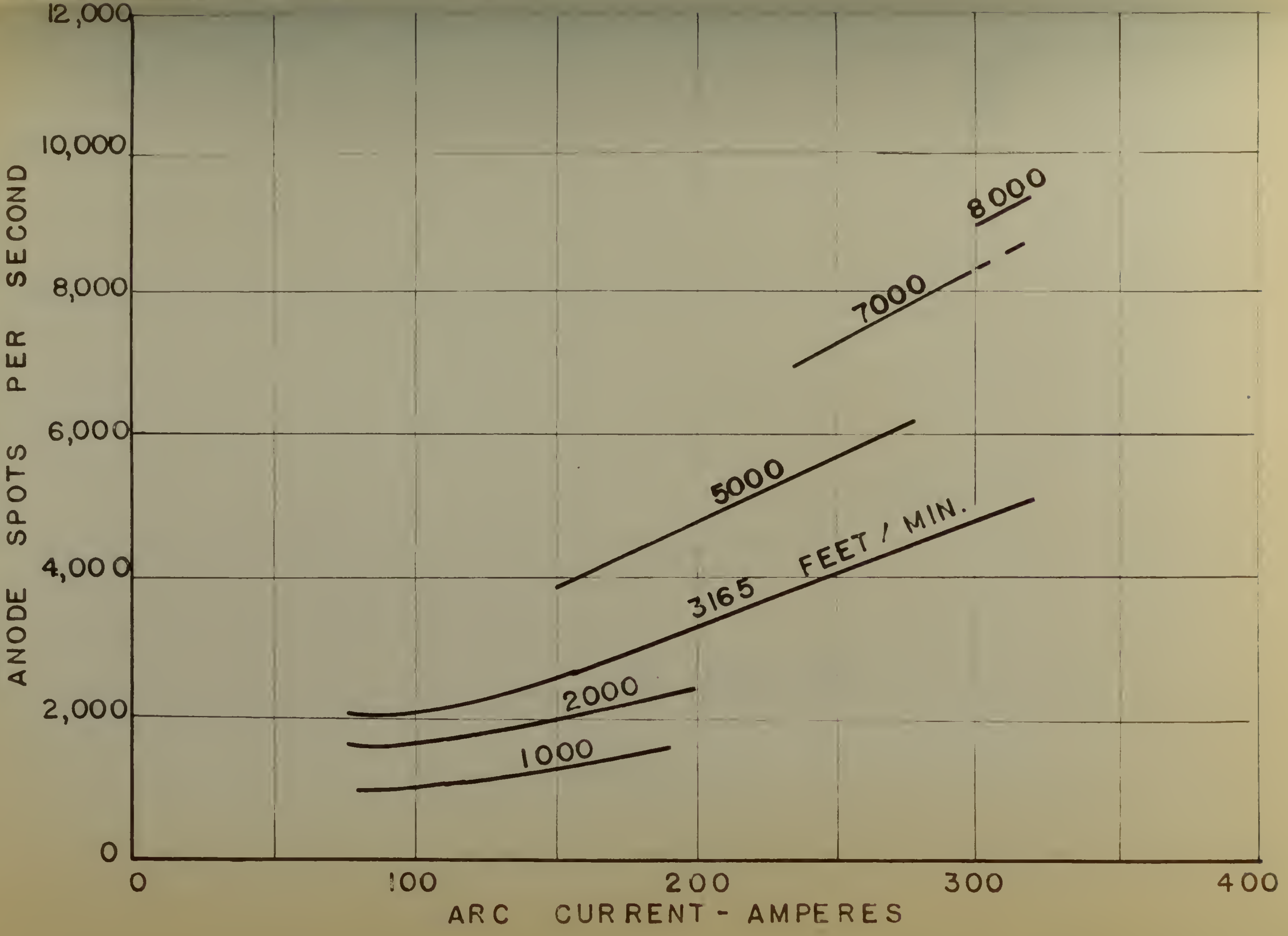


FIGURE 20 VARIATION OF ANODE SPOTS PER SECOND WITH ARC CURRENT FOR ALUMINUM ANODE

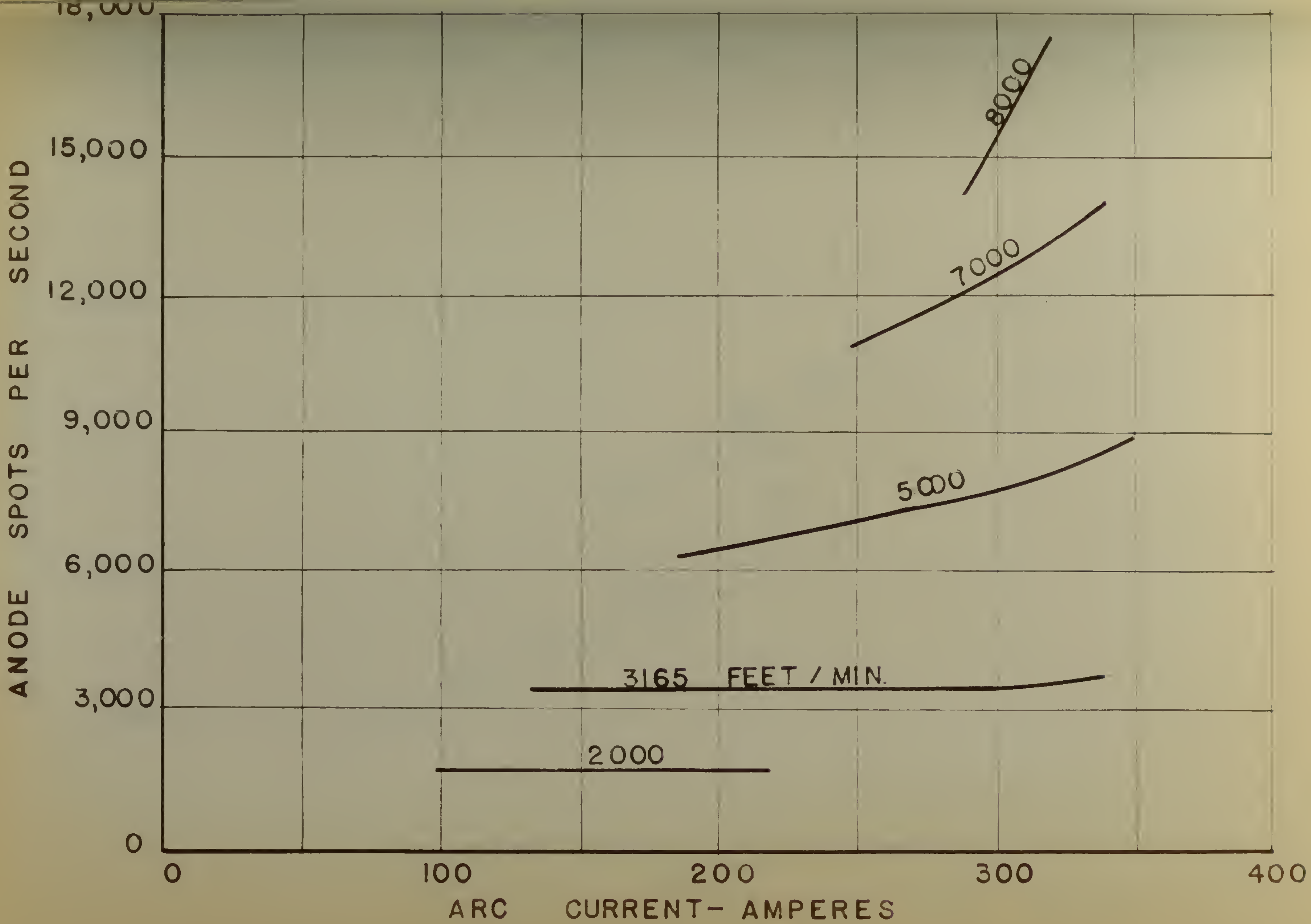


FIGURE 21 VARIATION OF ANODE SPOTS PER SECOND WITH ARC CURRENT FOR COPPER ANODE

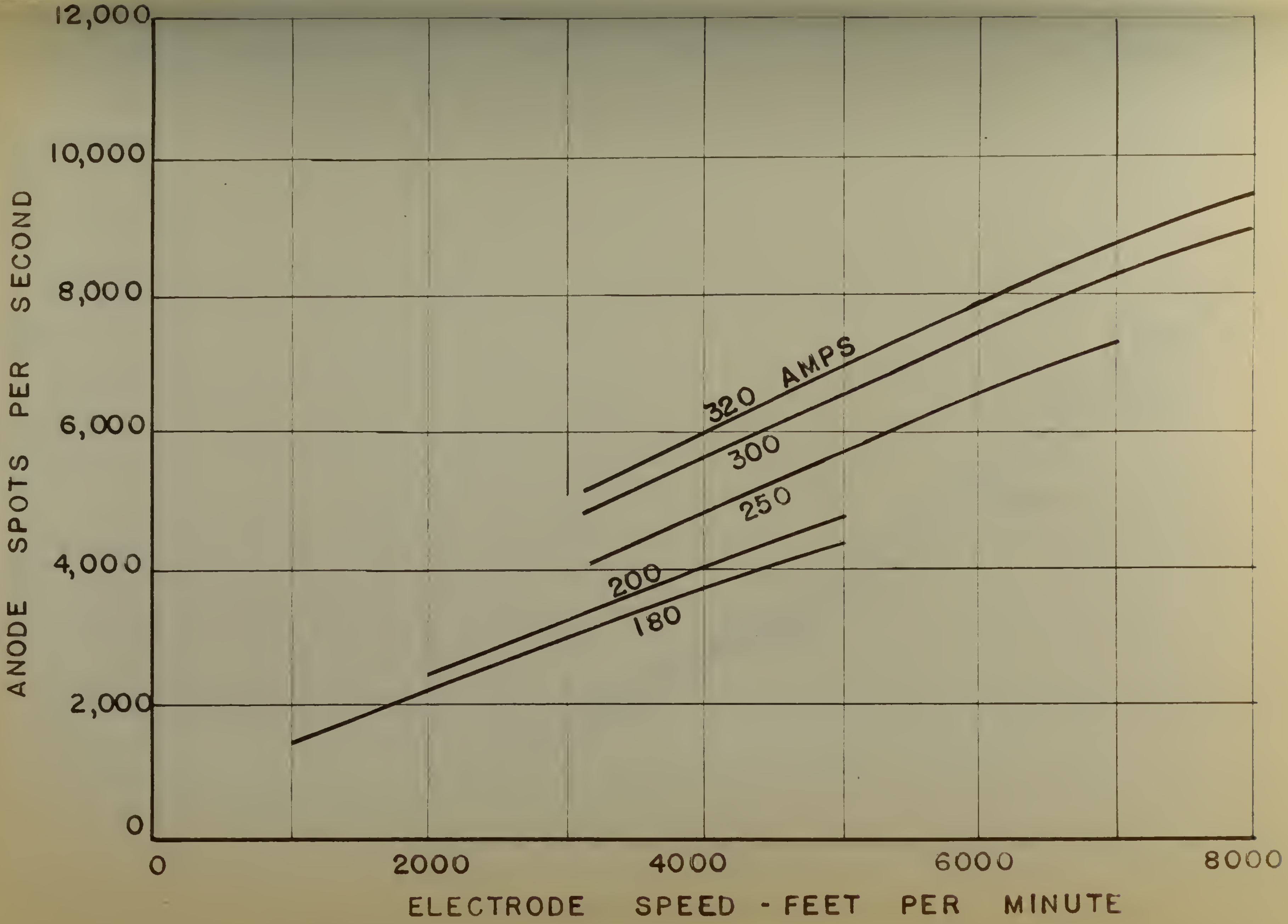
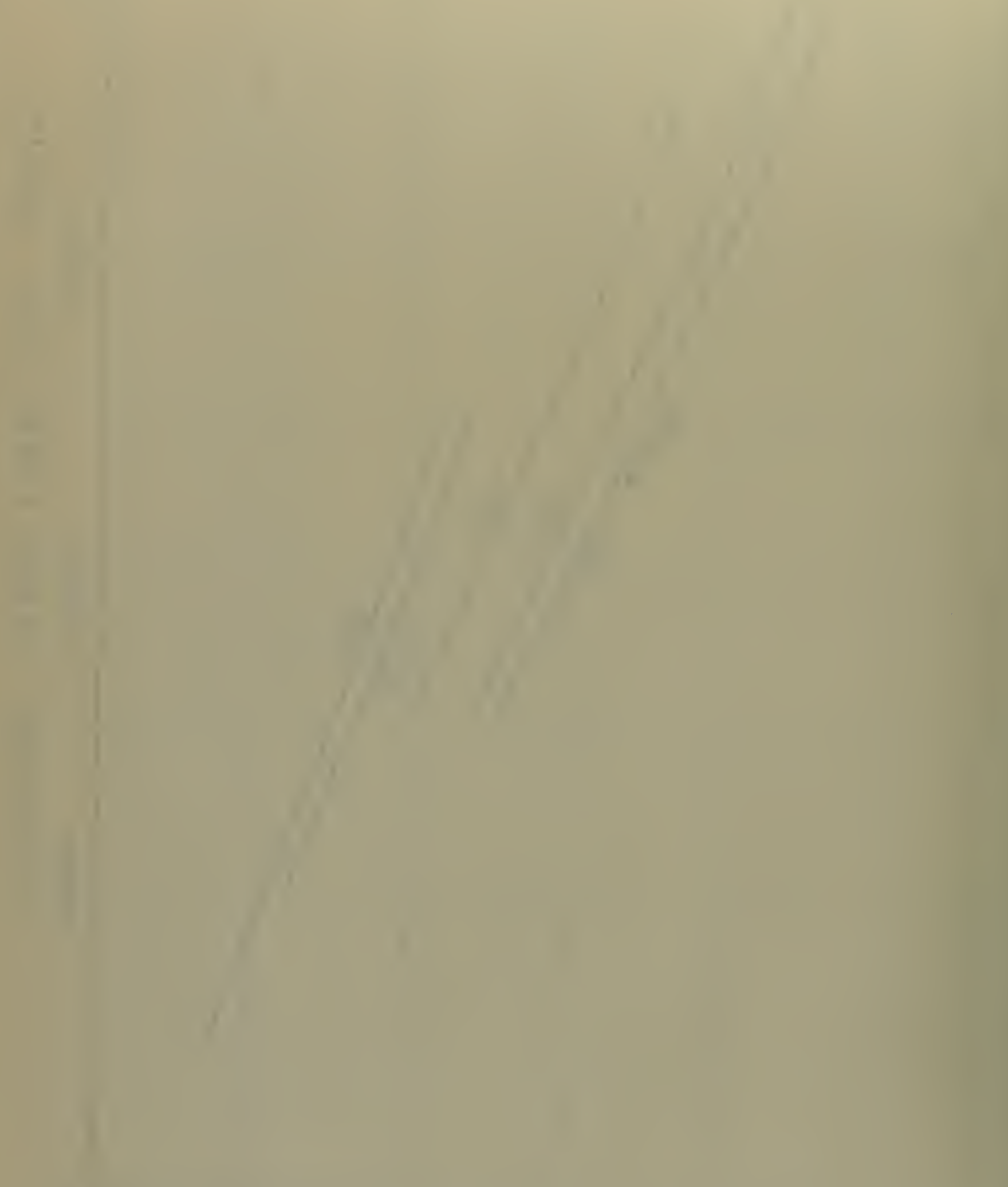


FIGURE 22 VARIATION OF ANODE SPOTS PER SECOND WITH ELECTRODE SPEED FOR ALUMINUM ANODE



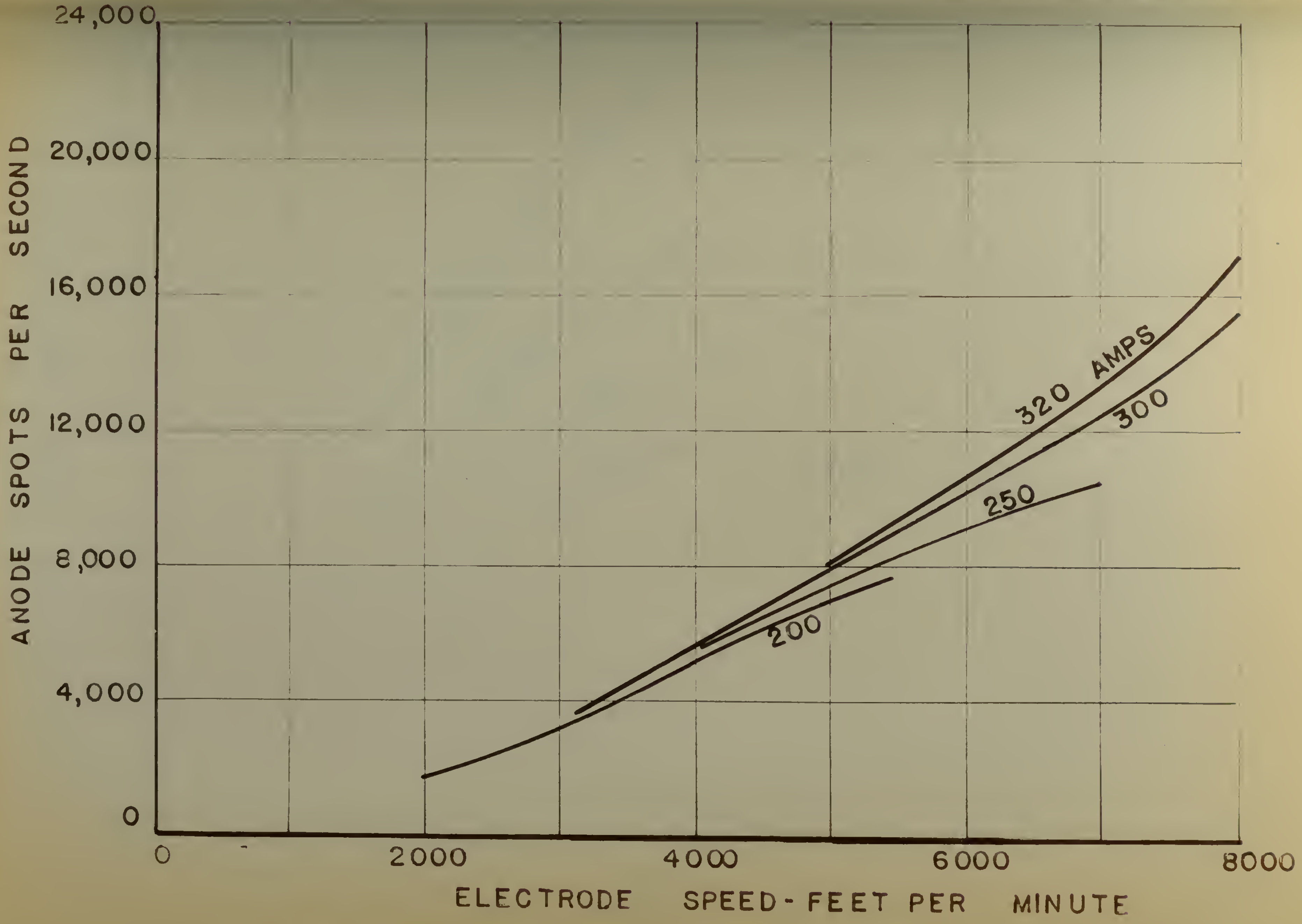
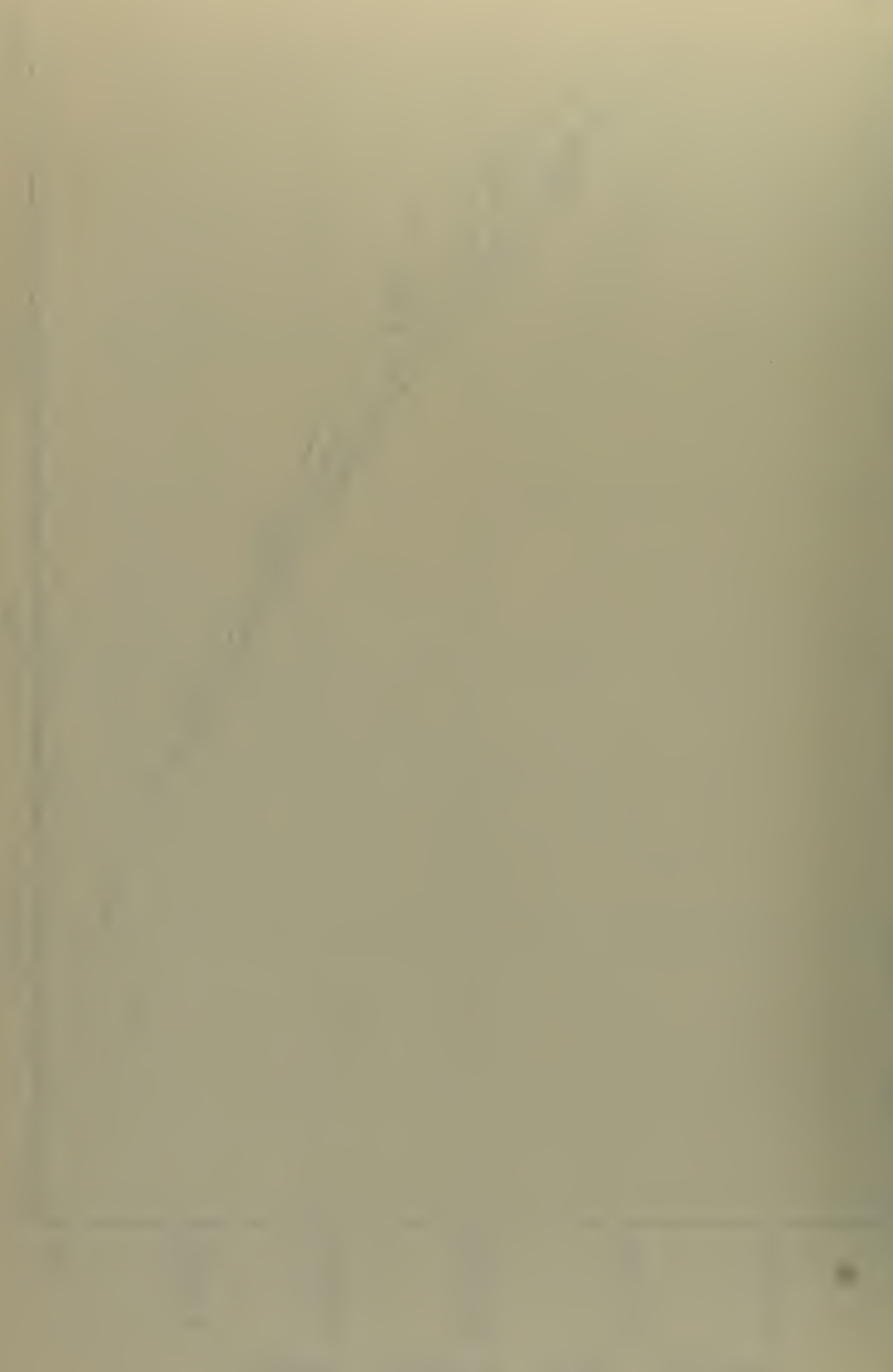


FIGURE 23 VARIATION OF ANODE SPOTS PER SECOND WITH ELECTRODE SPEED FOR COPPER ANODE



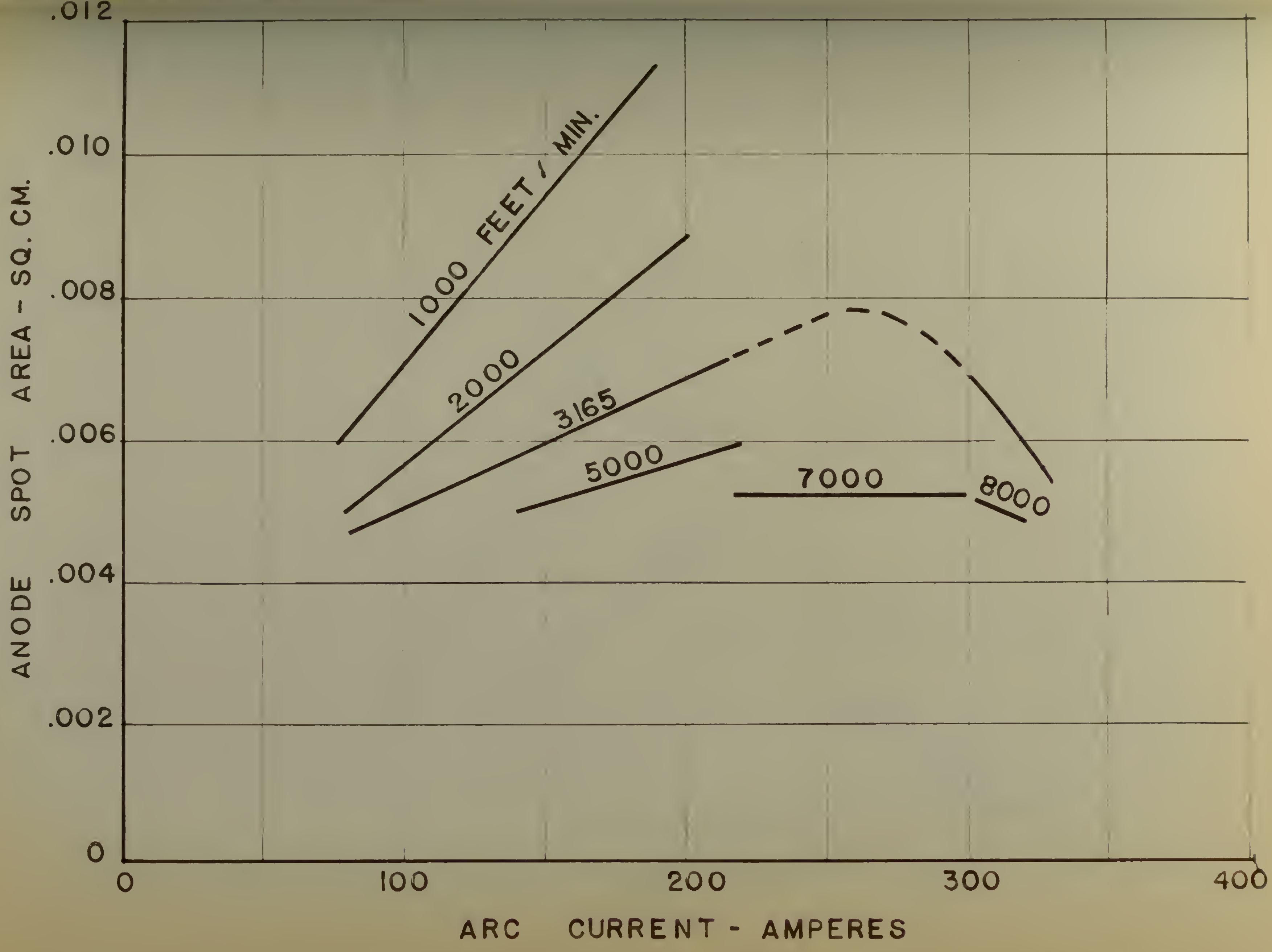


FIGURE 24 VARIATION OF ANODE SPOT AREA WITH ARC CURRENT FOR ALUMINUM ANODE

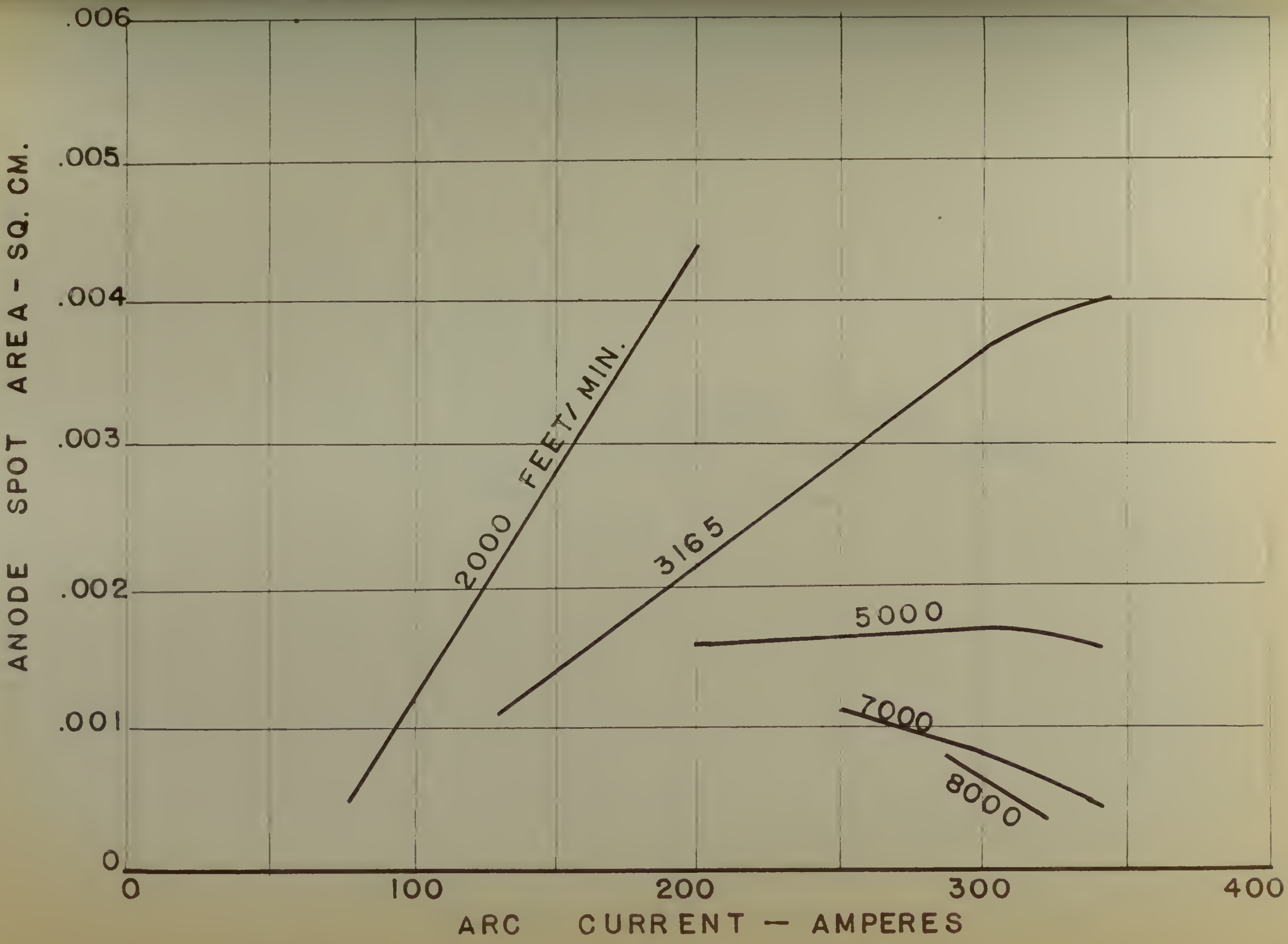


FIGURE 25 VARIATION OF ANODE SPOT AREA WITH ARC CURRENT FOR COPPER ANODE

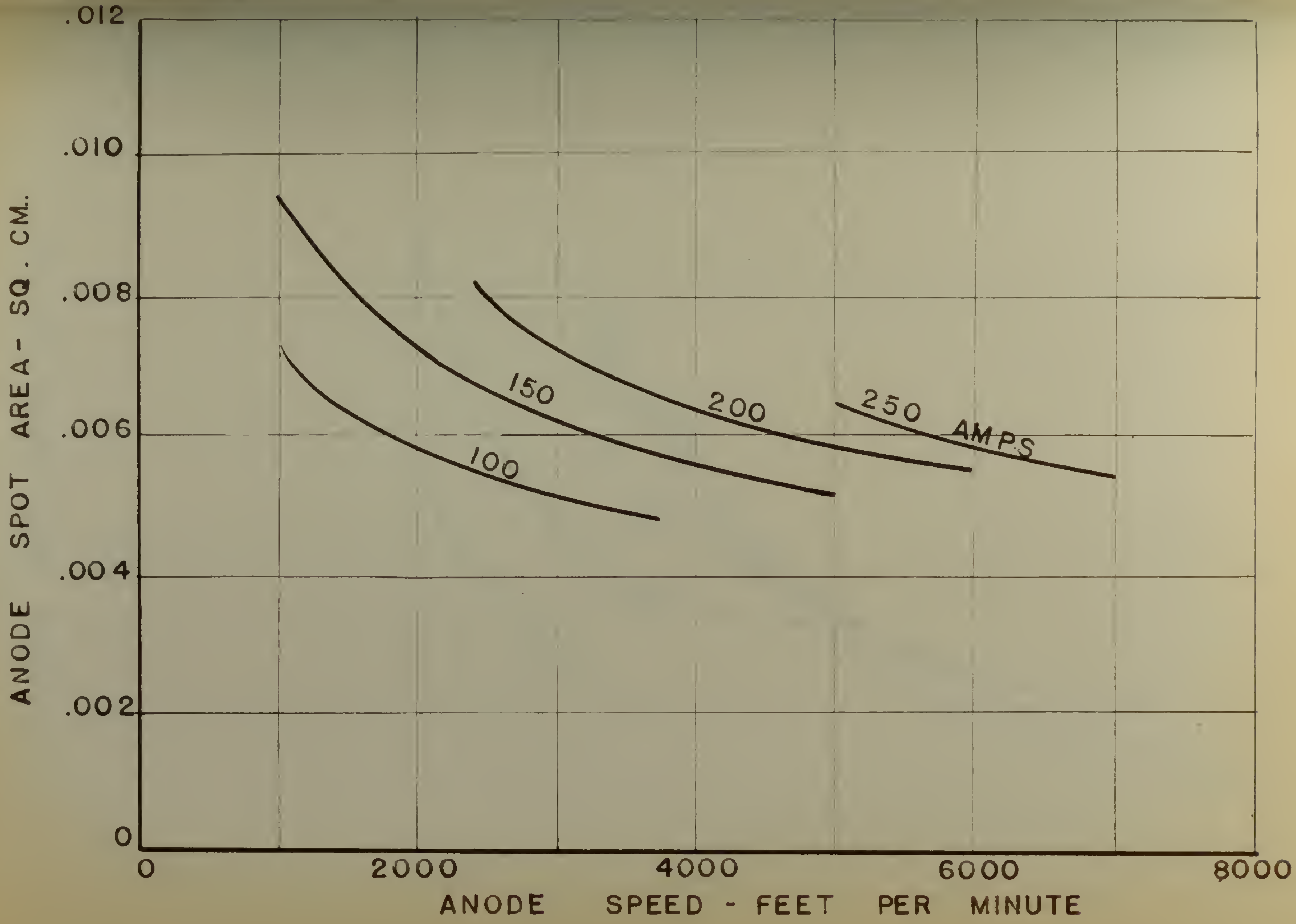


FIGURE 26 VARIATION OF ANODE SPOT AREA WITH ELECTRODE SPEED FOR ALUMINUM ANODE

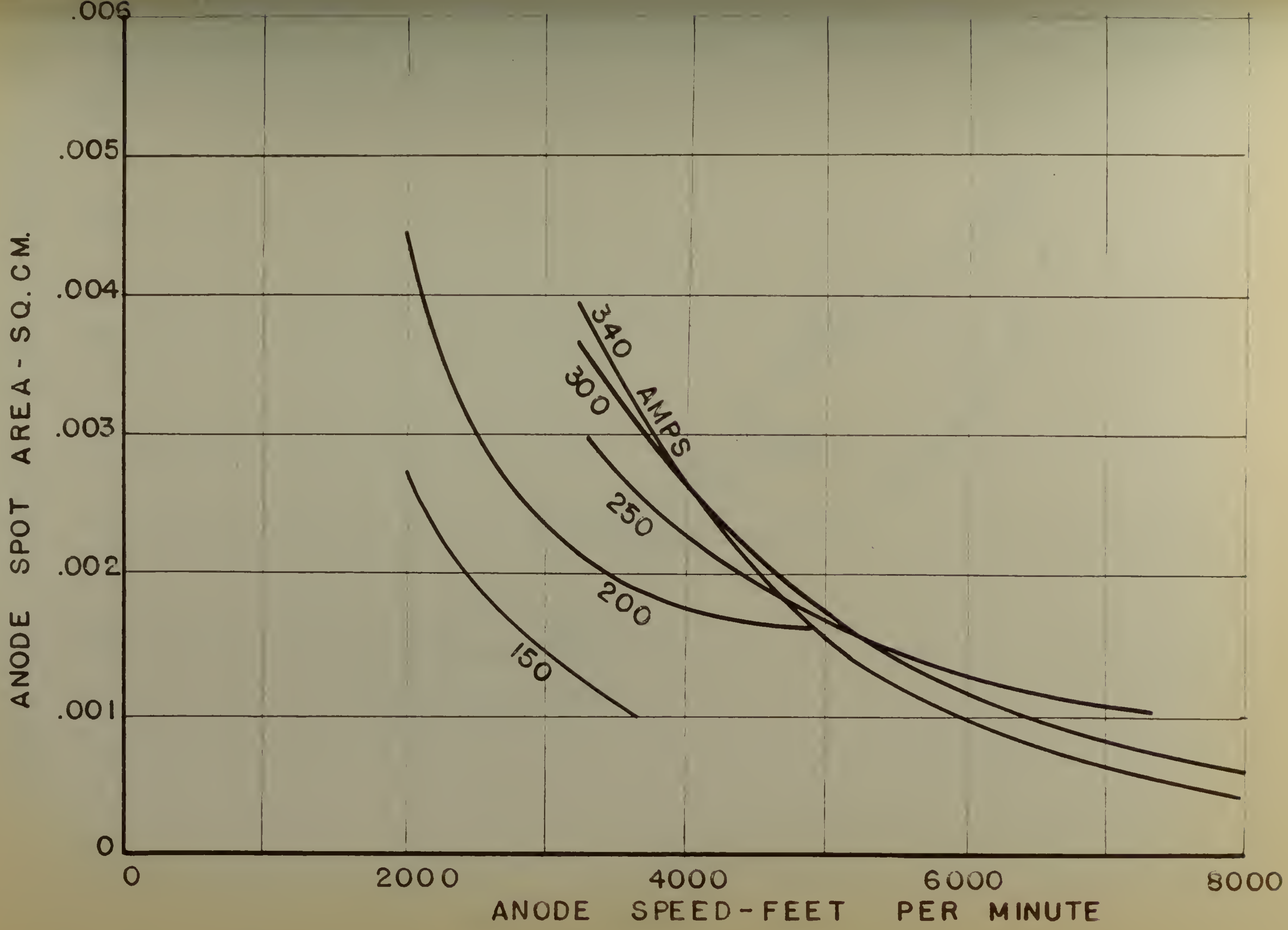


FIGURE 27 VARIATION OF ANODE SPOT AREA WITH ELECTRODE SPEED FOR COPPER ANODE

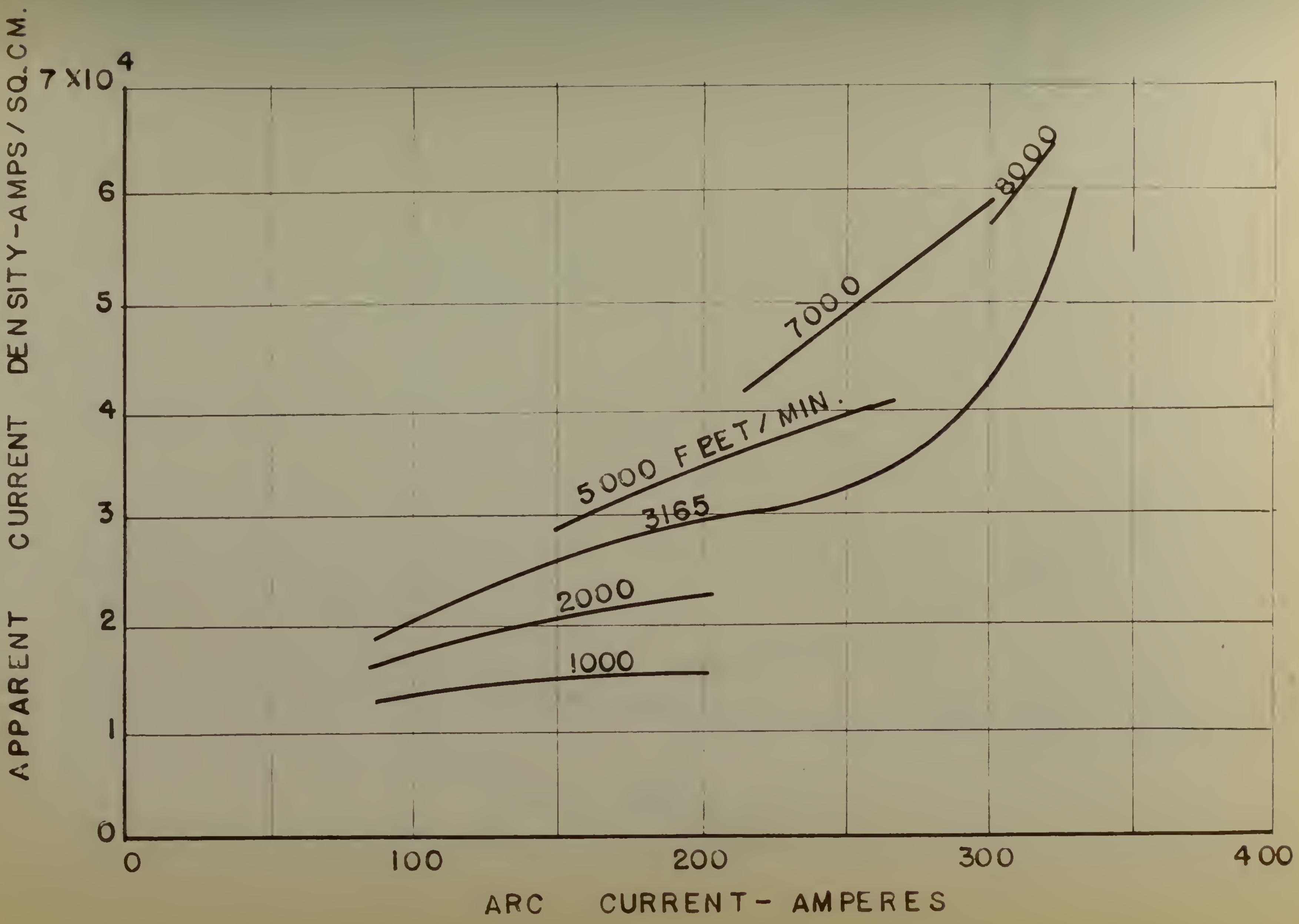


FIGURE 28 VARIATION OF APPARENT CURRENT DENSITY WITH ARC CURRENT FOR ALUMINUM ANODE

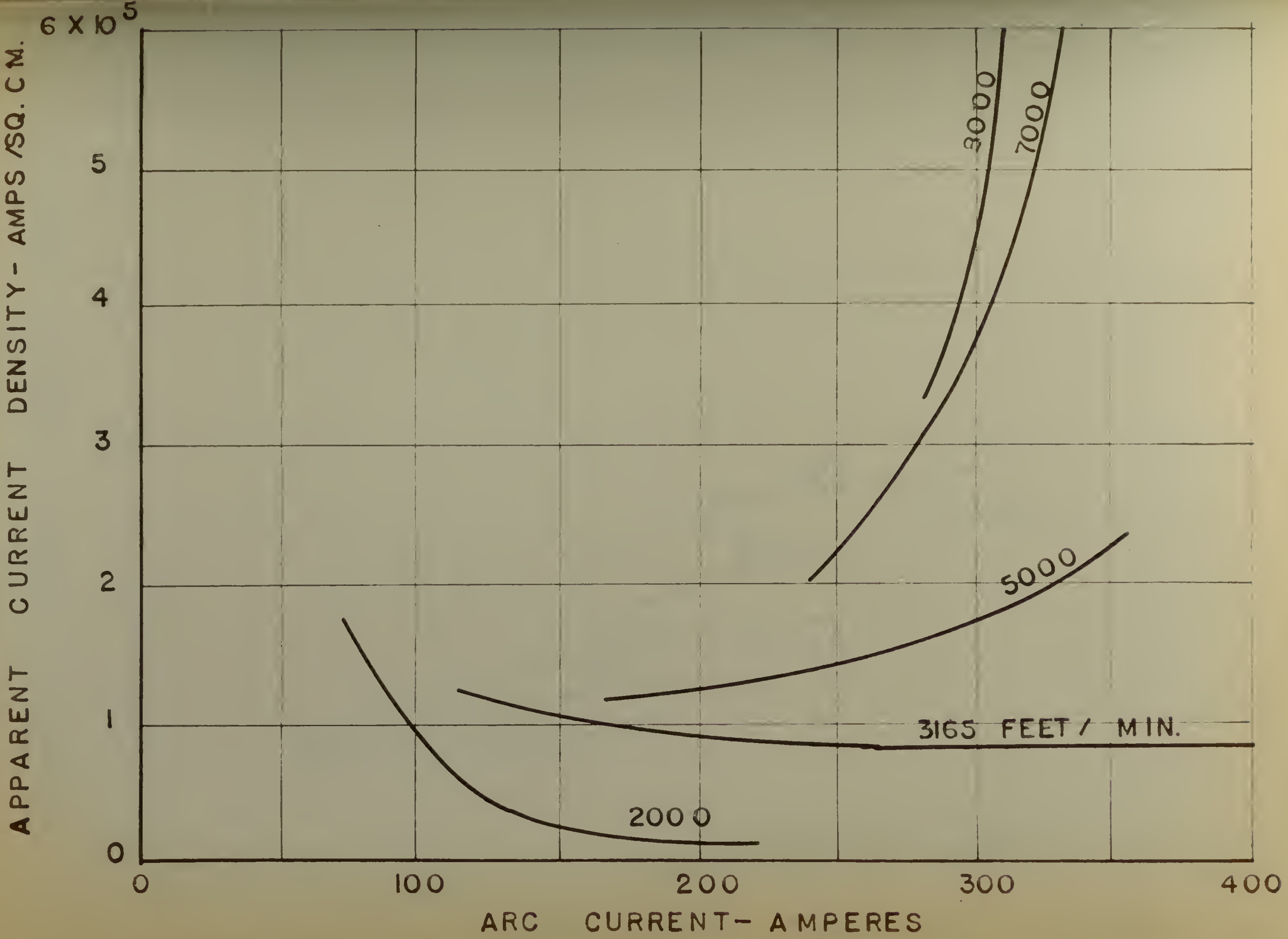


FIGURE 29 VARIATION OF APPARENT CURRENT DENSITY WITH ARC CURRENT FOR COPPER ANODE

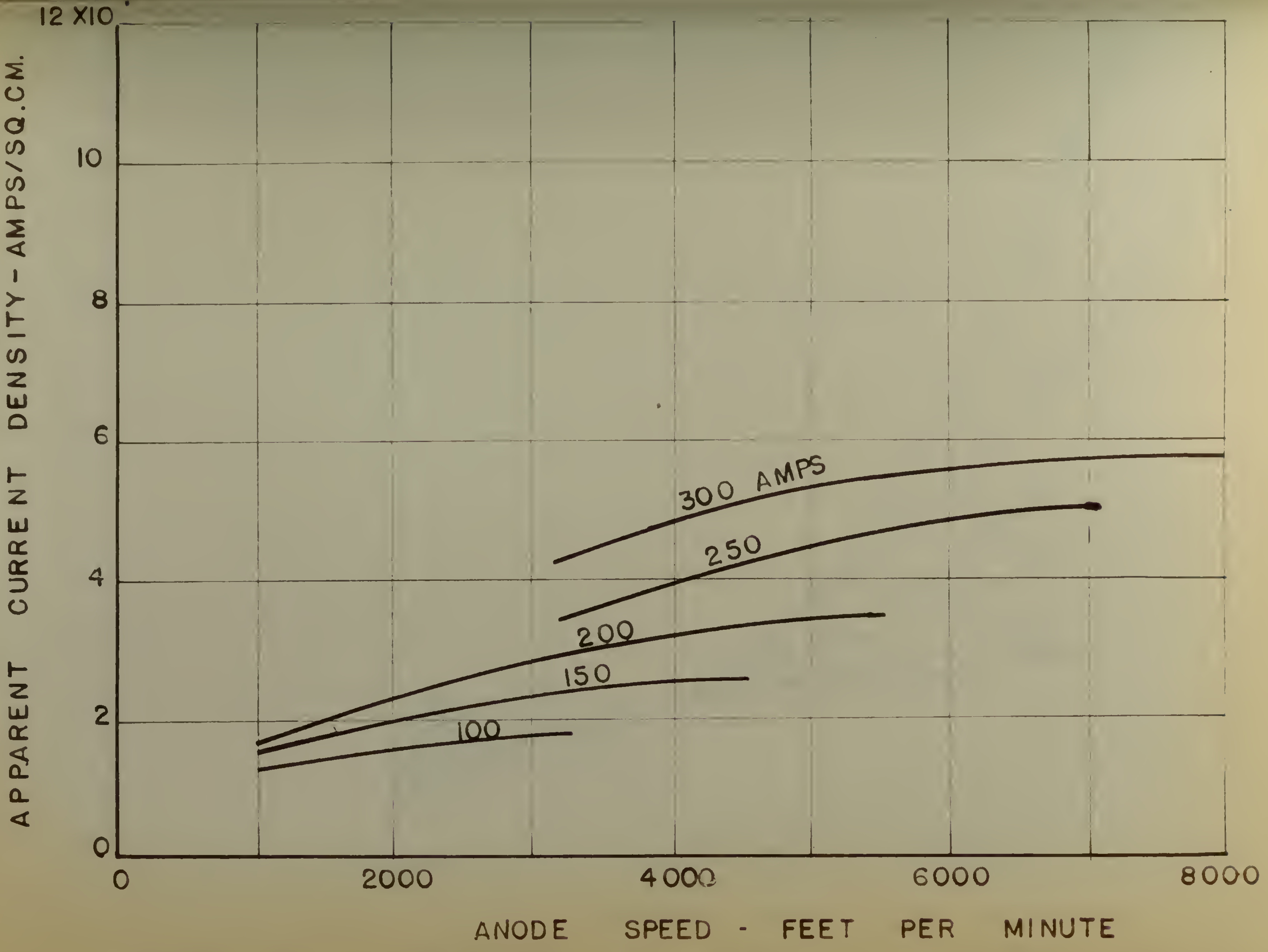


FIGURE 30 VARIATION OF APPARENT CURRENT DENSITY WITH ANODE SPEED FOR ALUMINUM ANODE

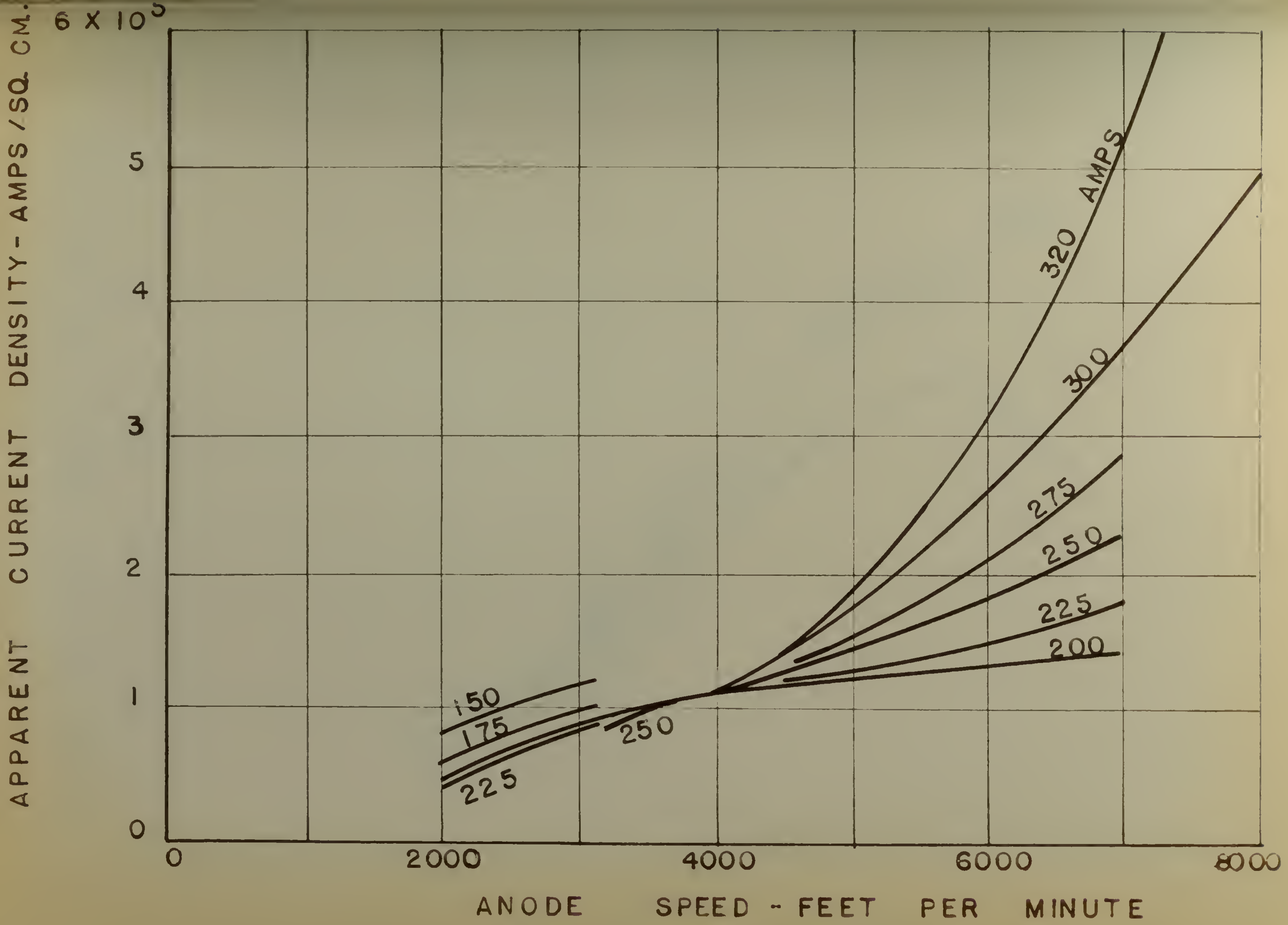


FIGURE 31 VARIATION OF APPARENT CURRENT DENSITY WITH ANODE SPEED FOR COPPER ANODE

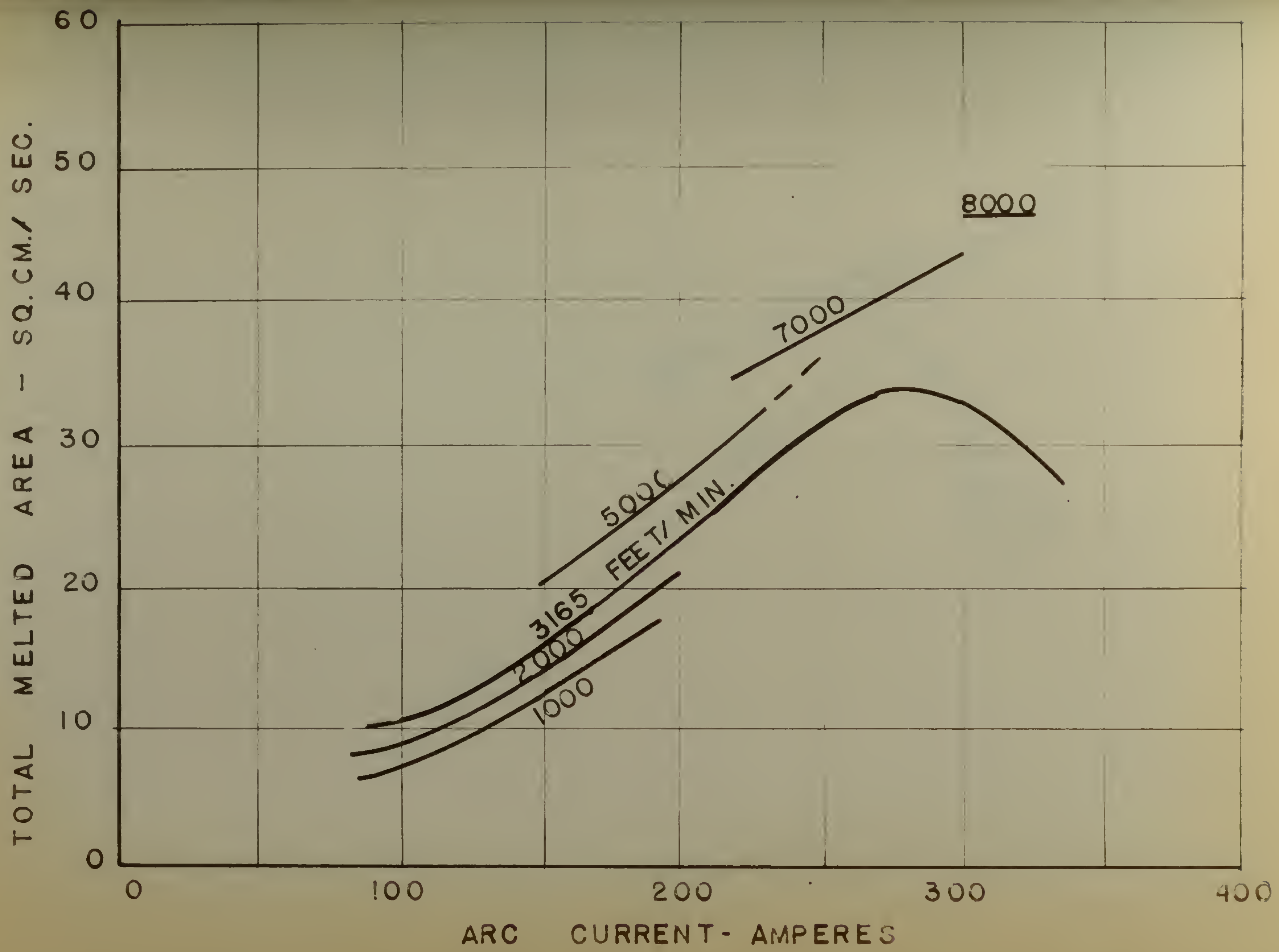


FIGURE 32 VARIATION OF TOTAL MELTED AREA PER SECOND WITH ARC CURRENT FOR ALUMINUM ANODE

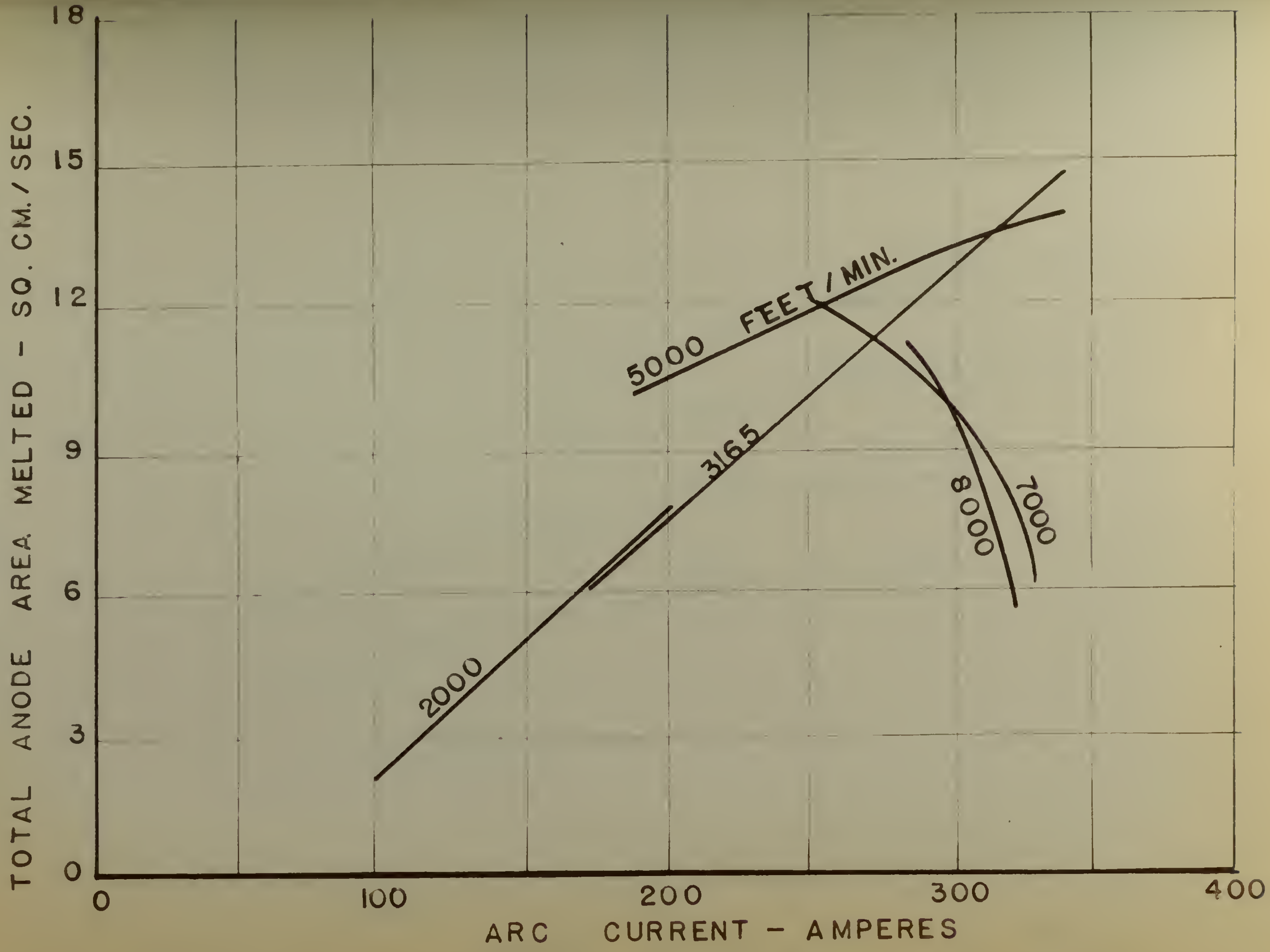


FIGURE 33 VARIATION OF TOTAL ANODE AREA MELTED PER SECOND WITH ARC CURRENT FOR COPPER ANODE

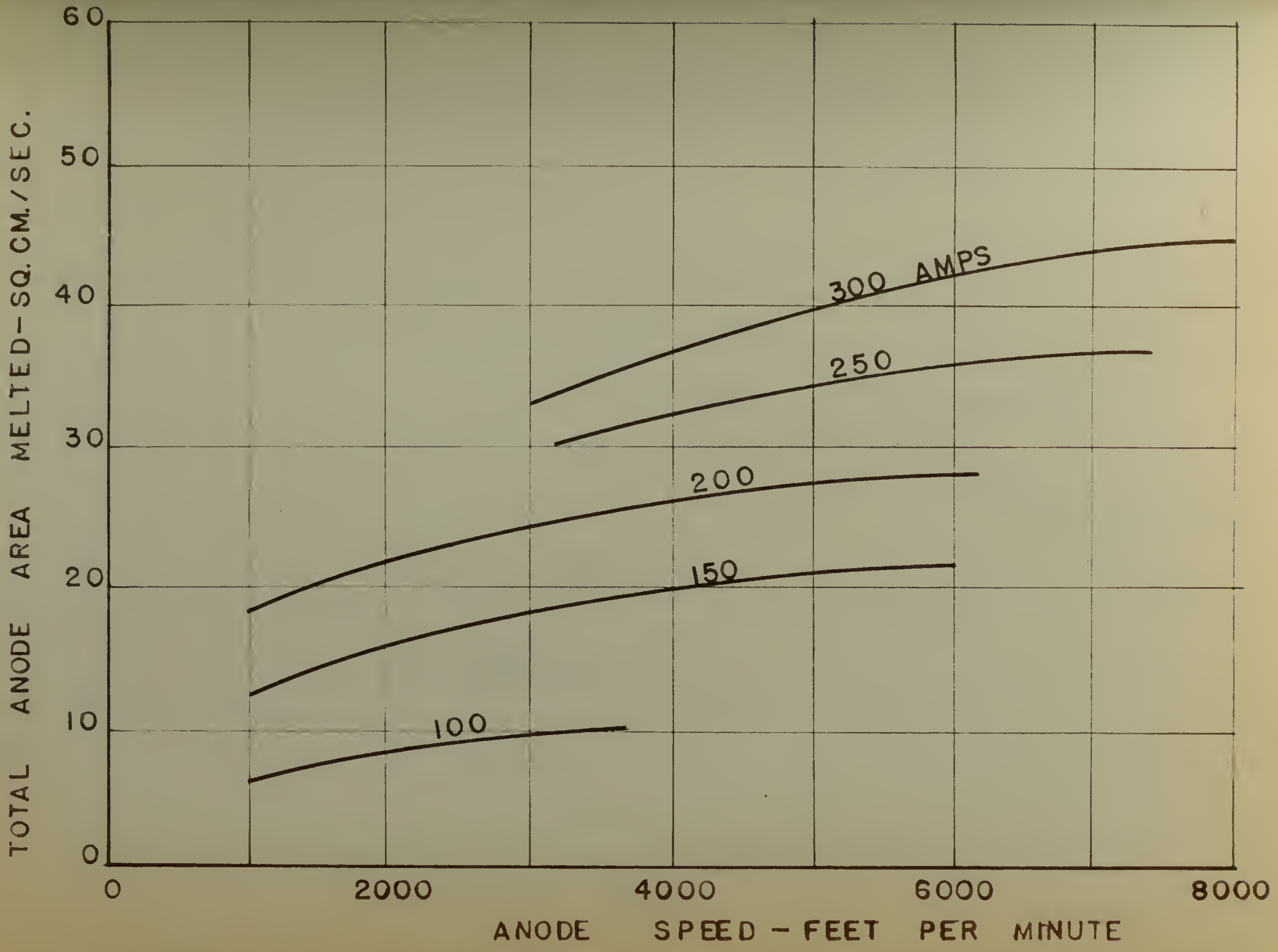


FIGURE 34 VARIATION OF TOTAL ANODE AREA MELTED PER SECOND WITH ARC CURRENT

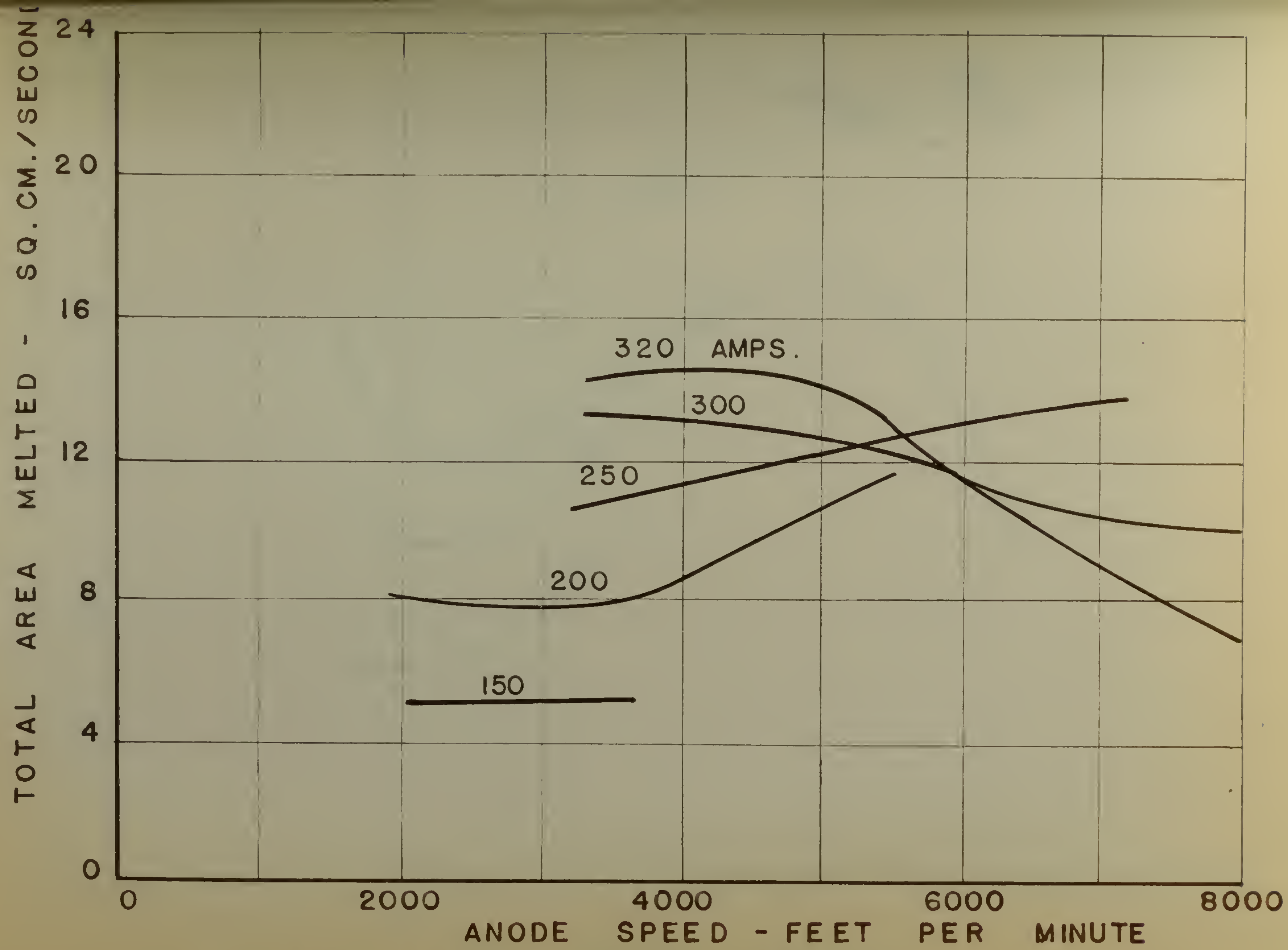


FIGURE 35 VARIATION OF TOTAL AREA MELTED PER SECOND WITH ELECTRODE SPEED FOR COPPER ANODE

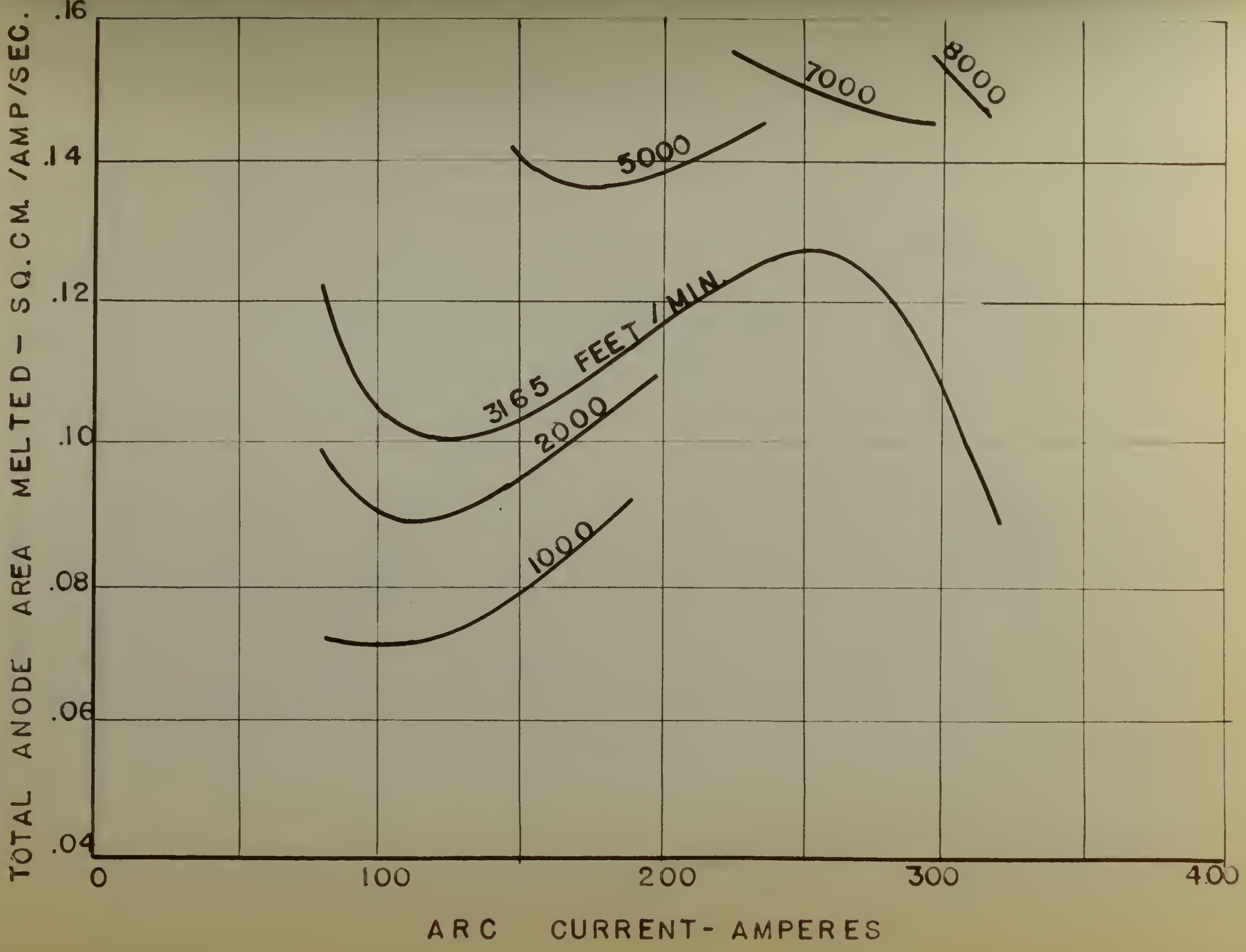


FIGURE 36 VARIATION OF TOTAL ANODE AREA MELTED PER AMPERE PER SECOND WITH ARC CURRENT FOR ALUMINUM ANODE

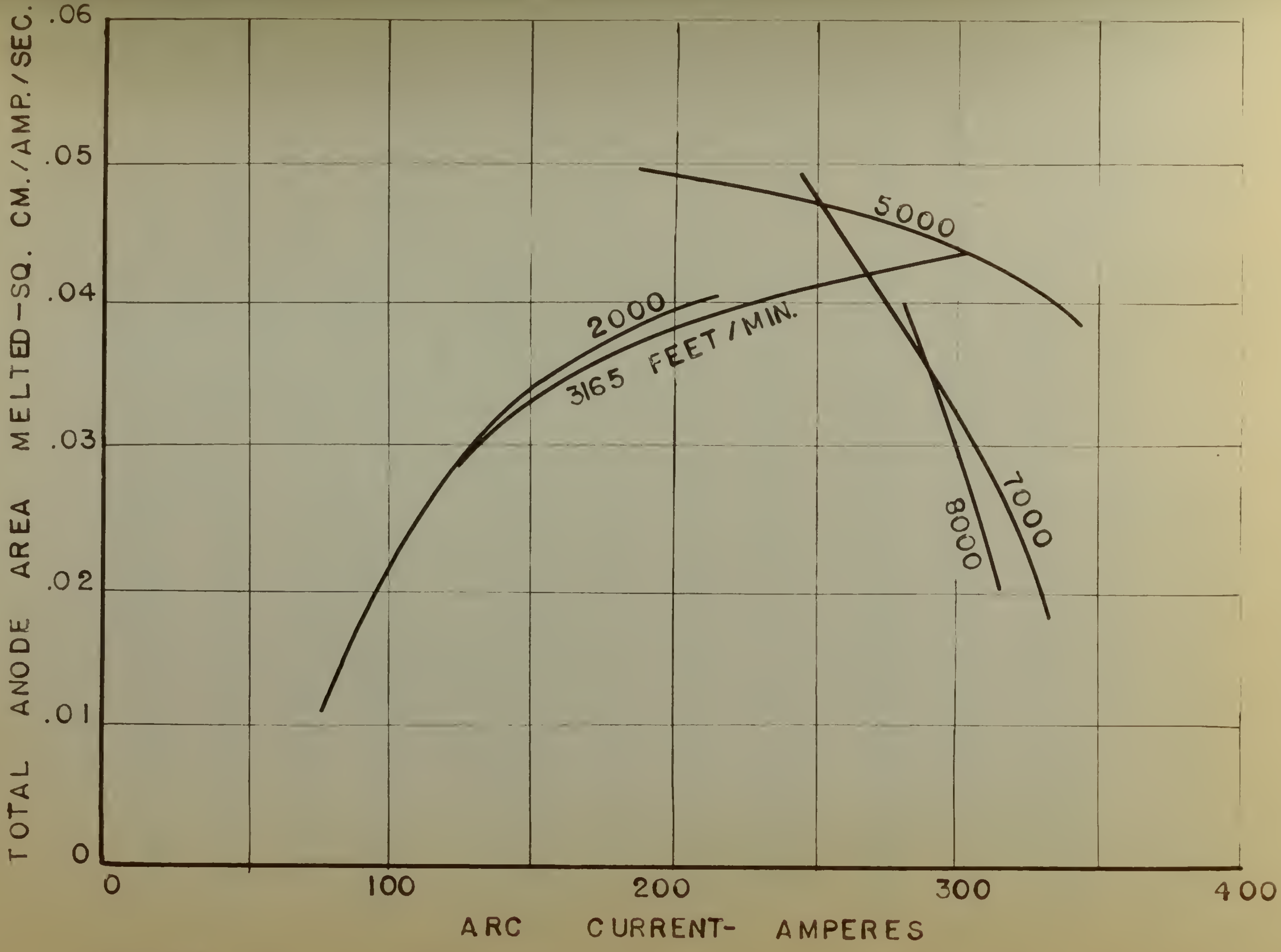


FIGURE 37 VARIATION OF TOTAL ANODE AREA MELTED PER AMPERE PER SECOND WITH ARC CURRENT FOR COPPER ANODE

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27. Kouwenhoven, W.B., Jones, T.B. and List, B.H,,PAPER PRESENTED MIDDLE EASTERN MEETING AIEE, October, 2, 1950, Baltimore.

VITA

The author was born in Holyoke, Massachusetts on July 18, 1919. He obtained his early dducation in the public schools of that city, completing in June of 1936. He was employed in the local industries of that city from 1936 to 1939. In 1939 he entered the United States Naval Academy an Annapolis Maryland. In 1942, upon the completion of the course of instruction at the Naval Academy, he received his Bachelor of Science Degree and was commissioned an Ensign in the United States Navy. During 1942 and 1943 he served in the Atlantic Fleet of the United States Navy, during which time he participated in the support and prosecution of the amphibious landing in North Africa, Sicily and Italy. From 1944 to 1946 he servec in the Pacific Fleet of the United States Navy and was employed in the defence of the Aleution Islands, the liberation of the Philippine Islands, the siege and capture of the Japanese RUI KIUIS Islands and the aerial siege of the Japanese homeland. During 1946 he travelled extensively in Japan and participated in the Japanese War Crimes Trials. After short tours of duty at Boston and Newport, in 1948 he reported to the U.S. Naval Postgraduate School at Annapolis Maryland to resume his formal training in engineering. In June of 1949 this Institution awarded him the Bachelor of Science Degree in Electrical Engineering.

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